# The Dee-in-Valley Radio-Frequency System at UCLA

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Dr. Richardson has just listed an interesting set of requirements that a good r-f system should meet. Such performance is what the "customer" wants from the r-f engineer, and I think it is safe to say that it is seldom what the customer gets. [Laughter] .

The only thing that keeps the r-f engineer's job from becoming a near impossibility is the fact that sparking puts a limit on the dee-to-liner gap. In rare instances gaps have been increased to lower the r-f power, but in most cases the gap is set by sparking probability and the r-f engineer must somehow provide the desired dee voltage with a minimum of power within this limitation. Some loosening of requirements may occur if this minimum power gets excessive, say around a half megawatt, not because of the difficulty of the job, but because costs get prohibitive. With the deck stacked as it is, the r-f engineer can hardly expect to have things his own way, but at least he should not allow himself to be intimidated by the customer. [Laughter] .

At UCLA we have gone well beyond the usual sparking limits imposed on magnet gaps by using a unique dee design. What we have done, I think, may be an introduction to what seems to me an almost inevitable pattern for large machines of this type. You saw the pictures of the dee structure presented in earlier talks by Dr. Richardson and Dr. Wright, and probably noticed there was room for electrodes in the spaces between the ridges. As mentioned by Wright, we started out with the idea of putting the iron in the dees in order to get large flutter. We were hard to discourage. We didn't give this up until we had bent several pieces of iron pretty badly out of shape. At the same time we discovered that the fields we could obtain, which were up to 26 kilogauss, were a lot higher than I think most people expected.

Figure 131 is a photograph of the model of the dee and dee-stem structure which is going into the UCLA machine. The upper and lower sections of the dee are approximately an inch apart and are held at the edges by the dee stems. The dees fit in between the iron ridges, which are shown mocked up by pieces of wood partially covered with thin copper. Only two dees will be used. The angle of the transit is about 45°, plus a little more because of some fringing, and we expect to obtain between 0.4 and 0.45 of the voltage again per turn that you would get with 180° dees. Dees of the 180° section are very inefficient as far as acceleration is concerned. The portions way out at the edge do not contribute very much to the acceleration, store a lot of energy, and take a lot of power.

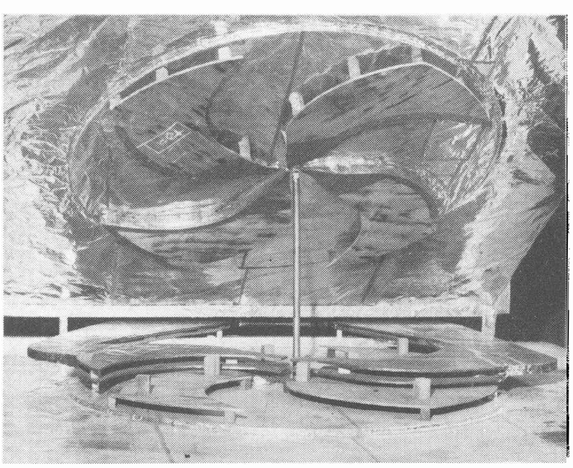

Figure 131. Spiral-dee r-f system at UCLA, full-scale model of plywood covered with copper and aluminum.

We were forced into this design once we had decided to use a 1-in. gap over the iron hills. Such a small gap is very desirable to get square flutter for maximum focusing and also good deflection probability. With a 1-in. gap you do not have any room for a dee over the hills that will let any beam through if you allow any space for sparking; whereas with the dee in the valley you have a good 1-in. gap dee-to-liner and still an inch of space for the beam. Our model tests show that we will obtain something like 50 or 60 kv on each dee with a power input of around 30 kw, which is very moderate. The gaps are large enough to allow probably up to 100 kv on each dee if we wished.

Dr. Richardson has given a figure of 17 kv in the dee as a threshold to overcome the field errors that are expected. With more than double this figure we don't have to trim as accurately with the coils. In many laboratories concerned with spiral-ridge designs a lot of effort has gone into trying to shape the field so that the dee voltage can be lowered as far as possible. Sparking, power, and general belief that r-f is still a black art make most people hesitant to think in terms of any more dee voltage than absolutely necessary. With 180° dees most of these worries have good foundations, so I would like to point out what advantages the dee-in-valley design can offer as the size of the cyclotron increases.

The worry about field accuracies, and so on, or the magnitude of the job of trimming of the field, goes up in proportion to the size of the machine, or probably some power of the machine. When talking of a large machine around 400 or 500 Mev, the field rises 50 or 60%. To trim that field to 0.1% might be a very difficult job. Consequently, it would be very difficult to hold the dee voltage down to the order of 20 or 30 kilovolts. A machine as shown in Figure 1313, scaled up, will have very deep valleys. The spacing from dee to valley floor can go up to the order of a foot. With such clearances, calculations we have been making show that a given energy gain per turn can be obtained with the order of 1/10 the power required with 180° dees. A factor of 10 in power is a sizable item cost-wise.

Another factor to be reckoned with in large dee structures is the stored energy which is dumped into a spark; it will be faced by people who intend to build large machines with 180° dees. There is no experience whatsoever that I know of to indicate exactly where the threshold comes in stored energy. Stored energy in a spark will start at some point to locally melt the surface. Some of you may know some of the history of the 184-in. cyclotron. Before the synchrocylotron principle was discovered, Dr. Lawrence planned to overcome the relativistic problem by simply putting on more dee voltage; 1,000,000 volts on each dee didn't worry him. Someone calculated that if the stored energy was dumped in one spot, it would melt about a cubic centimeter of copper, and he immediately decided to make the dee liners 1-in. thick. [Laughter]. Now whether or not you can lick the problem in this way is rather questionable. Some experience at Livermore with a large linear accelerator showed that at some point the stored energy will melt any material you care to try. Where this limit is I don't think anyone is willing to say, but it could be that continuing with larger and larger dee structures will eventually result in reaching such a limit.

I should also point out that the small-gap machine will be cheaper than a large-gap machine, and I think that by following through on its development we will be advancing the art of accelerator design. After our machine is working I think it will be not as easy to raise money for designs using more "conservative" ridge geometries where the dees cover the hills. I have put the word "conservative" in quotation marks, since the probability of deflection is greatly increased by using a very small magnet gap, and in this sense the dee-in-valley system would be labelled conservative.

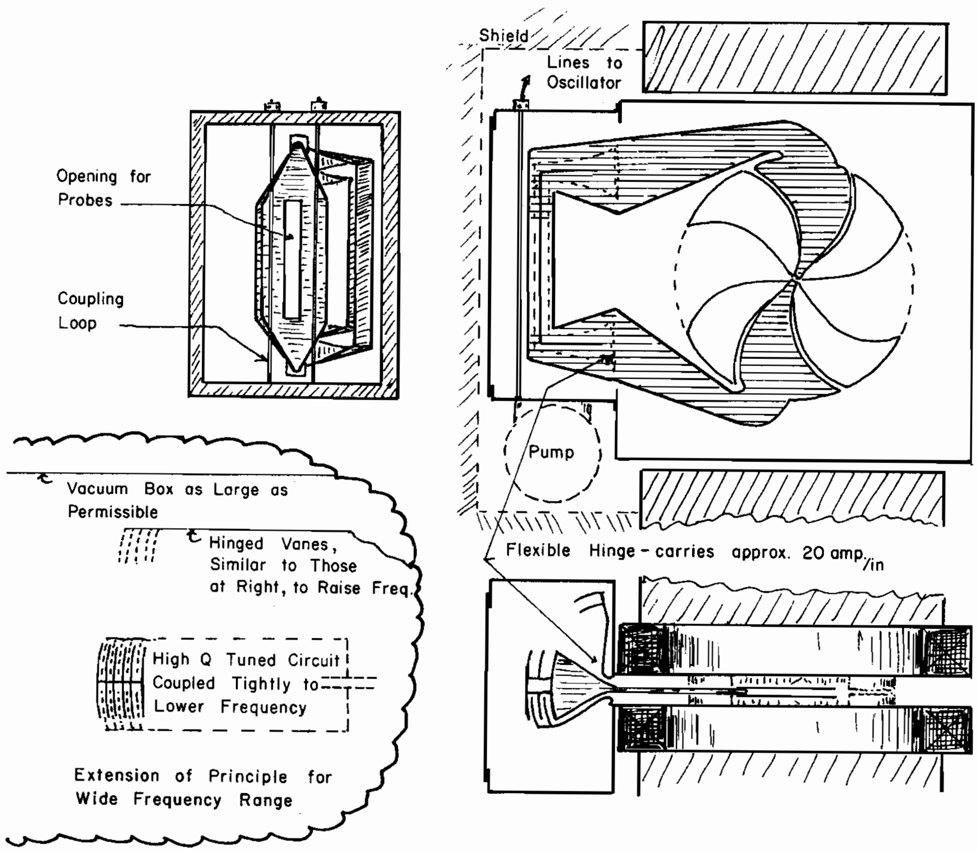


Fig. 132. UCLA spiral-ridge r-f system. The upper and lower grounded liner vanes can be meshed symmetrically with the dee-stem vanes. The position of maximum inductance is illustrated by the upper vane, and the position of minimum inductance is shown by the lower vane.

Figure 132 shows a plan view of the UCLA cyclotron r-f system, with the two dees in opposite valleys, leaving two valleys free for all kinds of other things. One does not gain any factor worth mentioning by using four dees. Actually, the largest transit effect comes with the ions crossing the center of the dee at zero voltage.

Now I would like to present some general design features of the r-f system which I believe were brought out in some previous papers. The vacuum box in which the dee assembly fits is beyond the control of the r-f engineer. This is set by the magnet shape, the proximity of coils, etc. For magnet efficiency these factors should be optimized without due regard for the r-f system.

Operating within these restrictions of small gaps and spacings inside the dee vacuum chamber, the r-f engineer must lead the dee stem from the dee to the edge of the vacuum chamber with as little loss as possible. To do this the stems are made flat and flare out as they approach the edge (Fig. 132). The flat stems add extra capacity, of course, and more charging current will be required, but the increased surface area provided by the flare keeps the loss low. The transition to the outside region is at a point just outside the coils of the cyclotron. At this point the vacuum box can be made much larger. The losses that are incurred in this outside section can be made as small as one wishes by making the vacuum box as large as possible. It is here that the r-f engineer should insist on his rights. He should persuade everyone to make that box as big as possible within reason. Twenty feet by twenty feet is not out of reason at all in certain cases. [Laughter].

In our own case we have some internal restrictions. Dr. Richardson has access to portions of an old battleship, in the form of class-B armour plate, which we plan to put around the magnet, for shielding, and this restricts the outside space. Actually there is no point in making the box very large for our machine because the power is very low anyway.

We plan to vary the frequency somewhat. At first we planned to vary it so the energy could change by a factor of two, which means a factor of $\sqrt{2}$ in the frequency. This was to be done in a very simple way, by simply cutting out inductance in the outside region with a system which we have worked on independently at both Berkeley and UCLA. It is a modification of the "barndoor" principle that originated with Donaldson at Oak Ridge. The liners simply come clost to the stems and cut out volume, thereby reducing the inductance. The difficulty with the "simple barndoor" is that the current density goes up as the spacing is reduced because the current rises with frequency, and therefore the power goes up as the square of the current if the surface area remains the same.

The scheme we are working on is to increase the surface area in proportion to the square of the current which is flowing; this happens to turn out very nicely to be an automatic process. If you mesh the vanes on the grounded liner with the vanes on the dee stem, (Fig. 132), the impedance goes down inversely proportional to the increase in area. If you have all your inductance in the outside box where you can work on it, (which is not quite true of course since even the flat stems have some inductance), you theoretically can change the frequency without increasing the power over and above the power you would have at the highest frequency. If the outside box is made larger and larger, you can decrease the outside power as far as you wish. In principle there is a theoretical limit where all the power you are using in the machine is represented by the loss inside the dee vacuum chamber.

In Figure 132 we note that as the outside box gets larger and larger the lowest frequency, obtained with vanes completely unmeshed, becomes correspondingly lower. There is essentially no theoretical limit to the amount of frequency range obtainable with this system. Obviously some practical limit exists. To find out something more about such limits we are setting up a model which will have no application toward our 50-Mev cyclotron but may provide useful information for others and possibly outselves in the future.

The present plan for the frequency range at UCLA is somewhat more modest than a factor of 2, since, in the interest of getting a beam as soon as possible, we are not worrying about variable energy. We will take what we get. The frequency will be variable in the manner described above but will be somewhat short of the factor 2. We estimate that 25 to 30% variation will be adequate for initial tune up and will provide more range in the r-f than in the magnet.

Figure 133 is a conceptual sketch of the wide range scheme mentioned earlier. The dee stems extend quite some distance back from the dee face plate. Some dees are sketched in the background, and the dee stems are flared out to a large linear dimension at the entrance to the large box, which would lower the current if hinges were used, (incidentally the hinges we plan to use on our 50-Mev cyclotron are simply

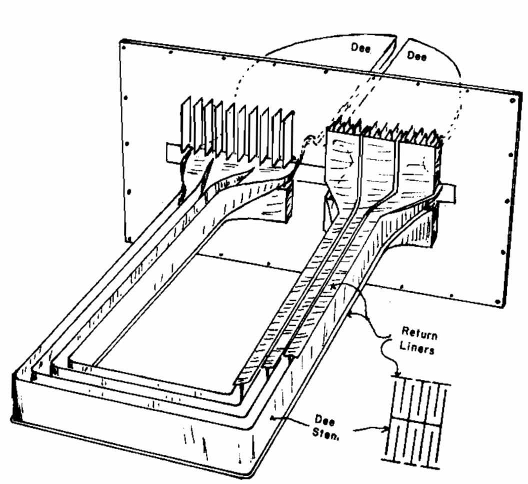


Fig. 133. A possible way of extending the meshing-vane principle, for very large frequency changes. The upper vanes are shown cut away.

flexing copper sheets and will be described by B. Smith in a following paper). Shown in figure are the liners which mesh with the dee stems. The ground current flows on these liners when they are meshed and, as you can see, the impedance will be very low. One can make this impedance as low as one wants by simply putting vanes in parallel until the surface area presented bothers the vacuum people, (assuming all these structure are in vacuum, of course). One can stretch the line arbitrarily a great distance for any given frequency by just tapering the spacing to a very small value at the node.

Shown is a liner which is split into three sections. It is just to give the idea. If you lift one of the sections out completely, the current flows on the remaining sections, and of course, the impedance goes up as sections are removed.

At the dee face plate is shown a scheme we intend to try out, which looks as though it ought to work fairly well. In place of hinges we have a large capacitor. The ground currents flow from the inside of the liner on to this capacitor, and equal and opposite currents from the other side of the capacitor flow along the liner. So one has a condenser or capacitor in series with the liner circuit. This opens up a very interesting possibility for variable energy. As long as you have hinges in this region and the liner simply decreases the inductance, you have a single tuned circuit. As soon as you install a capacitor you double the number of circuits. The liner, with a capacitor in series is a circuit, and so is the dee and stem.

When you have two coupled circuits the frequency range can be expanded greatly by using the two modes that occur when you have a tightly coupled system. One can never achieve unity coupling, but to separate the modes as far as possible you want to get the coupling as tight as possible. This scheme lends itself, as you can see, to very tight coupling. In fact, the longer one makes the stem the tighter the coupling.

The scheme then would be to have a median frequency where you have the liners removed completely. (In other words, you need a big box for this). The liners are moved out of the region of the long dee stem and you have a rather low frequency. If you mesh the liners and operate in what is called the antisymmetric mode, the currents in the liners will be flowing in the opposite direction from the currents in the dee stems. If you mesh them completely (cut out all the volume) and force all the currents to flow in between the vanes you will have a very high frequency, characterized primarily, in the limit, by the amount of inductance contributed by the flat dee stems in the region between the edge of the coil and the dee (inside the dee vacuum chamber).

Then we can go back and start all over again at this median frequency where the liners are decoupled from the dee stem. We then mesh the liners and operate in the symmetric mode in which the current in the liner and the current on the stem flow in the same direction. In this case the frequency will go down. If the two circuits are identical it will go down by a factor of $1/\sqrt{2}$. If the liner circuit is a much lower frequency than the dee circuit, (which can be achieved by a very large capacitor at the fact plate), then the frequency can be lowered even farther.

In this case the power losses are figured in a different way. The currents in the same direction on the liner and stem are balanced by equal and opposite currents on the walls of the big box, and there is a division between the current flowing in one circuit and in the other. In one special case the currents will be all on the outside of liners and stem, and no current flowing on the inside vanes whatsoever. This occurs when the currents in the two circuits are proportional to the outside surface areas of liner and stem. When the liner circuit is tuned to a lower frequency to achieve a greater frequency range, then the current division can no longer be that way. Some of the current on the outside ducks around the "corner," near the capacitor, flows back on the inside of the dee stem, comes around to the other capacitor, and flows around on the outside again. Here again the meshing of the two circuits gives a factor to our advantage. The currents flowing on the inside are doing no good whatsoever, but fortunately the large number of vanes makes the area large and the losses low.

One catch is that the currents have to do a little fancy stuff getting around the "corners," and this has been one of the big problems in all these frequency variation schemes. The arrangement in Figure 133 is, as far as I can see, the simplest way of getting around most of the problems where the currents have to flow into the meshed region and out again. The spreading of the dee stem makes it possible to take a large current from a large flat dee stem, and feed it into a meshed structure without local areas of high current or appreciable cross currents.

Now I should emphasize that this is not the only way to get wide frequency variations. A shorted line and shorting bars are conceptually very simple and might turn out to be the best way to do it if the mechanical and electrical problems of good variable contact are solved. They will be discussed in following papers.

I don't want to say anything in particular about coupling schemes to the oscillator They are fairly standard. There is no trouble in coupling either power amplifiers or power oscillators into systems like this.

Since we are talking about cyclotrons, frequency control is a question. It will have to be controlled in one way or another. If an oscillator is used, a frequency servo will be needed. If an amplifier is used, the frequency problem is solved but a phase servo will be needed. I think whether you use a power amplifier or a power oscillator is entirely dependent upon the people who are involved. If people understand power amplifiers, they use power amplifiers; if they understand oscillators, they use oscillators.

The power amplifier has one advantage in starting; one can get over ion-lock problems by what is called slugging the grid with a huge signal. However, that is not unique. One can also do the same thing with oscillators by suddenly closing a switch in the plate circuit.

The main problems are in the resonator. Other speakers following me will bring out other troubles with resonators that I have not talked about.

SNOWDEN: I would like to ask how you propose to support the dees mechanically in this variable energy design.

MacKENZIE: Mechanical support can be achieved, I would say, with insulators in the vacuum. Insulating materials now have developed to the point where I think one can trust them to a degree one could not trust them before. The difficulty with insulators usually comes at the high frequency end and if one puts the insulator support right at the node for high frequency, it is not under any strain to speak of, and at the low frequency end I don't think there is any problem at all. The insulator can run uncooled in the vacuum if it is made of very pure aluminum oxide.