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RF Note #48

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Alternate RF Systems for Superconducting Cyclotrons

General

There are two fundamental problems with superconducting cyclotron rf systems:

1A. To keep the turn number reasonable, very large rf voltages are necessary and

2B. because the dimensions are small, access to the dees is very limited.
In the case of the K=500 machine at MSU, where an ion source in the central region is planned there is a third problem:

3A. the spacing from dee to ion source is such that sparking there will limit the dee voltage.

Our present design for the K=500 MSU machine is marginal in three respects:

1B. The dee stem short fingers have to pass 75 amps/cm, and therefore may burn up.

2B. The 1 cm spacing, dee to ion source, may not tolerate 100KV.

3B. The power coupling capacitor, with a spacing of 1/2 inch, and in a magnetic field parallel to the electric field, may spark excessively.

Then there are the mode problems. Now, after carefull deliberation, abetted, with two martinis, I feel that 1B is fundamental and the other problems can be solved, somehow.

Fingers

"The moving finger writes; and, having writ,
Moves on; nor all your piety nor wit
Shall lure it back to cancel half a line;
Nor all your tears wash out a word of it."

Thus spake Omar Khayyam, lo these thousand years ago. He was obviously prescient and knew even then that a finger didn't like to carry a lot of current. And although we cried about our fingers burning up,it didn't do any good. What to do?

Well, it is possible to replace fingers with clamps! First, a contact, even a finger contact, in order to be able to pass a lot of current, must make a very low resistance contact. Now copper oxide is an insulator, and all copper exposed to air will be coated with copper oxide. Further, it takes a force of

20,000 PSI to penetrate a copper oxide film. (This was proven by the author in 1950 for a very oxided film.) So one would expect that a very mild copper to copper force, of say less than 1000 PSI, would result in a poor contact and inability to conduct much current without burning up.

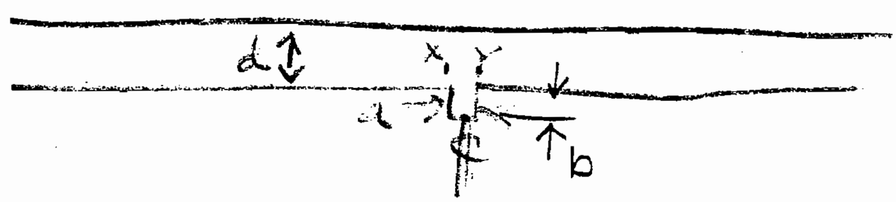
This was redemonstrated in an experiment carried out at MSU and documented in RF Note #9 . copper fingers on copper, with little force, were no good. Then we silver plated one of the surfaces and got remarkable improvement. So, against all theory and our better judgement, we went ahead with a design using silver plated fingers against copper.

Now silver forms both an oxide and a sulfide. However, both silver oxide and silver sulfide are good conductors, and so, although the silver may look black, it is still a good conductor. So theory says that a silver finger should not be used against copper, instead it should be silver against silver. But this would lead to galling, so one of the surfaces should receive a flash of rhodium.

Clamps

It is believed (and I say this with hand on the book) that if two silver plated surfaces are pressed together with a pressure of 20000 PSI, for electrical conduction purposes it is as though they were welded together and were one piece! For dc this works well, but with rf we must consider how the mating is achieved.

Consider the figure below:



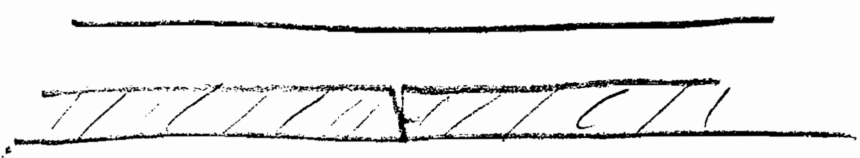
where we have a parallel plane transmission line carrying current I amps/cm at a freq F. The connection is made at C, but for mechanical reasons we have a depth b and width a in the process. At some current density (I) and frequency (F) the voltage across X-Y will be sufficient to result in sparking due to the $L \frac{dI}{dt}$ drop across this chasm. Let us work out an example to get a feeling for the problem.

Assume I = 100 amps/cm at 30 MHz, and d is such that the impedance of the line, per cem, is 1000 ohms. Now, away from the discontinuity the voltage difference per cm is

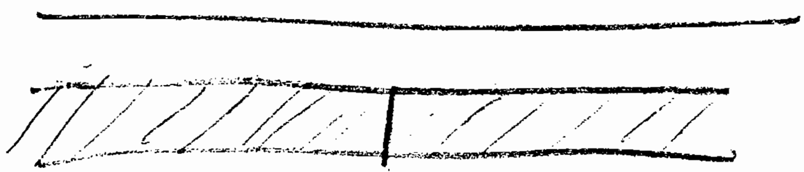
$$V = L\frac{dI}{dt} = \frac{100\,a\,Z_0}{C} = \frac{2\times10^{8}\times10^{2}\times10^{3}}{3\times10^{10}} = 700V/cm$$

and at the discontinuity it is increased by (1+b/d), which we will take as 1. Now if a=.01 cm then the voltage X-Y will be 70000 volts and we will have a spark down across L-Y. If a=.1cm then V(X-Y)=7KV and everying is O.K., as air will support a gradient of 30 KV/cm.

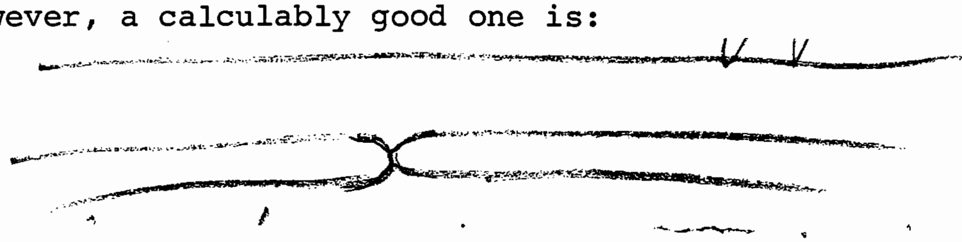
Now the purpose of the above presentation was to instruct mechanical engineers and others in the importance of making a "clean joint" vs a sloppy one. For example, on a microscale the joint below would be bad:



The correct one is



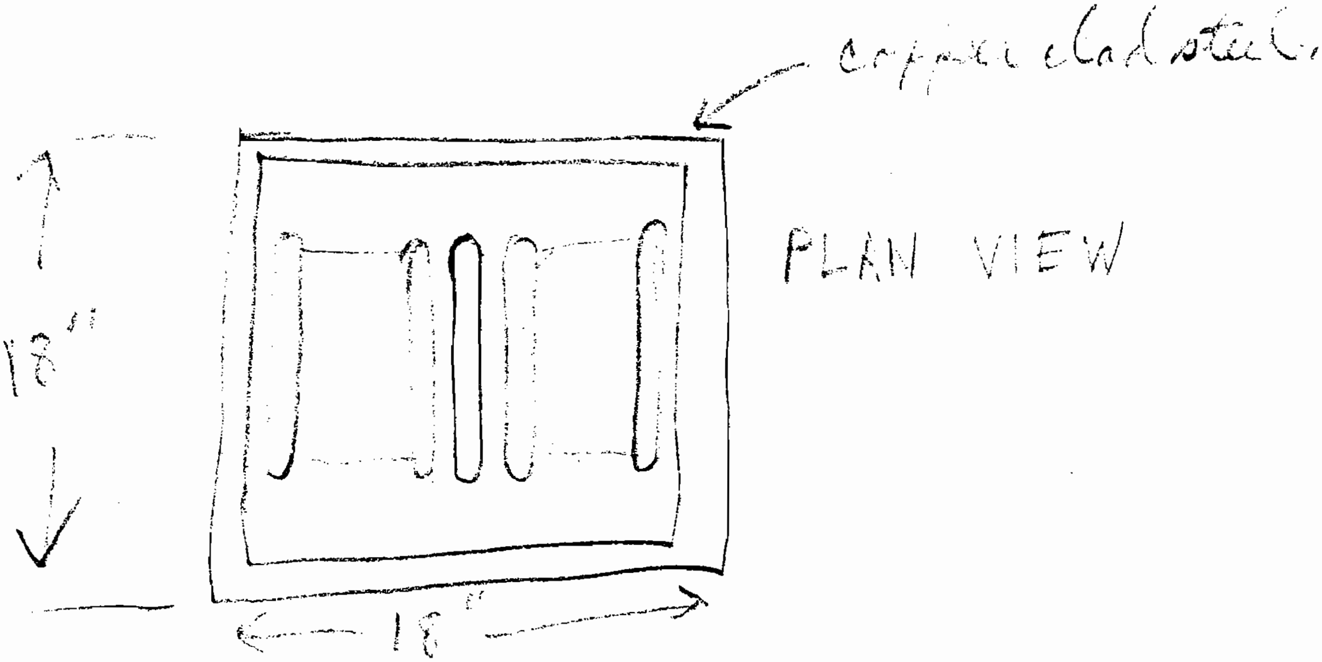
However, a calculably good one is:

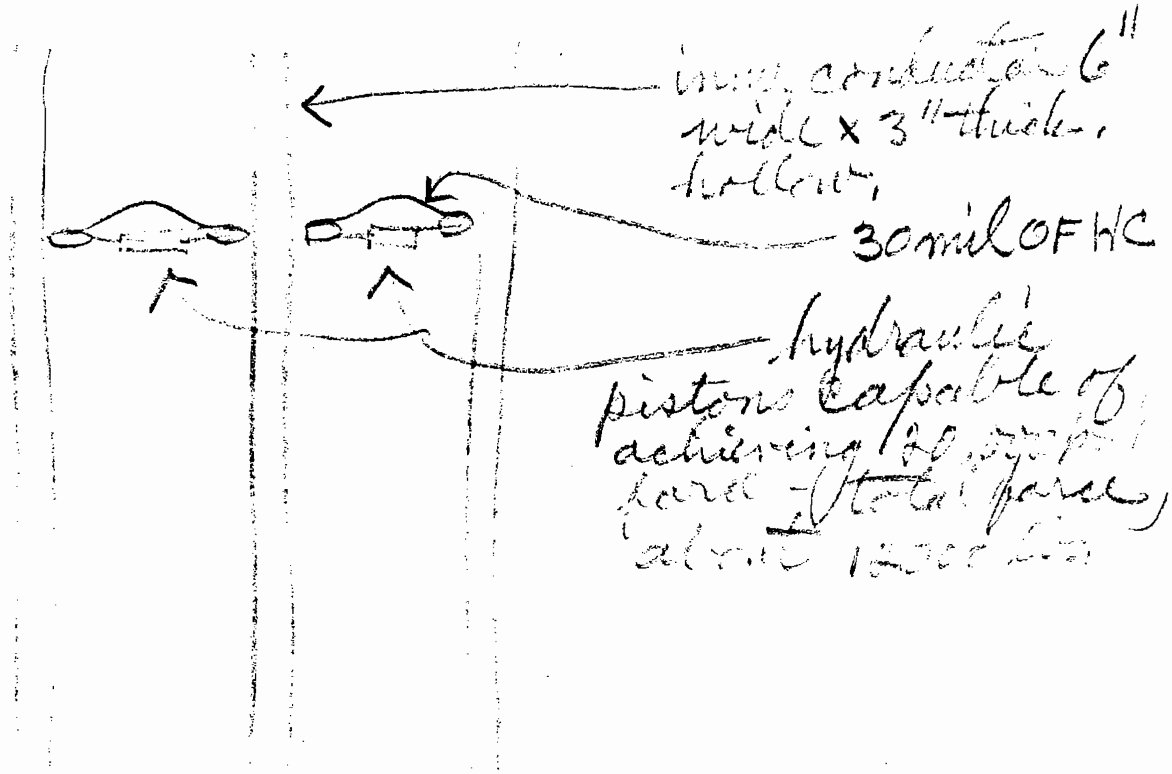


where the radii are carefully considered.

So now we can get back to <u>clamps</u>

Now in the beginning it was thought that moving fingers were good because it would permit facile movement from one "short" place to another close by. But calculations, and our experiences in test 1 & 2 show that with $\pm$ .2% ΔF capability from the fine tuner, the short position doesn't have to be determined to better than 1/4 inch. So we propose the following geometry for the moving short:





That's all for "Clamp".

The reason that 3A and 2B are not fundamental is that axial injection from an external ion source is always possible. 3B is not fundamental: we can easily build a coupler with more tolerance for high voltage. The reason we did not do so here was that this 1/2" spacing was certainly larger than the 1 cm dee to ion source spacing. Now for 2A and MODES.

Coupling Power to the DEE-STEM resonator

In the 1930's and 40's E.O. Lawrence tried using designs offered by the Electrical Engineering department of the University, and by commercial communication companies (Emerson Electric) to power his cyclotrons. These designs were copies of designs used to feed radio antennas, and involved a transmitter coupled to a remote antenna via a transmission line and various adjustable reactive elements designed so that the "load" terminated the line in its $Z\phi$, and offered a proper impedance to the transmitter tube. The results were disastrous. So in the early 40's a young nuclear physicist, K. Mackenzie, was given the job of solving the problem of powering a high circulating energy resonator. Quickly he saw that there was a profound difference between a broadcast antenna load and a "dee-stem" resonator.

I have gone over these differences before, so I won't elaborate here. Suffice it to say that he decided that A, the dee-stem resonator had to be the boss; B, the transmitter should be as close to the dee-stem resonator as possible; C, that the coupling should be strong; and D, that to minimize, modes, the number of circuit elements should be minimized. Using his criteria, many successful cyclotron rf systems were made throughout the world.

The K=50 MSU cyclotron rf system employed weak coupling, but the transmitter tube was less than 1/8 wave from the dee--so it worked, but with problems. Then there were linacs where a long transmission line was used between the transmitter and resonator--but these were single frequency machines and providing the line was an integral multiple of $\pi/2$ long it was as though the tube were at the dee, providing strong coupling was used. This is the method used at the Orsay DC1 and at SPEAR and other machines. People who use waveguides don't need to understand the desireability of using an $N\lambda/2$ line because they can use a circulator to prevent adverse reaction of the load back on the transmitter.

Building the transmitter tube in the dee

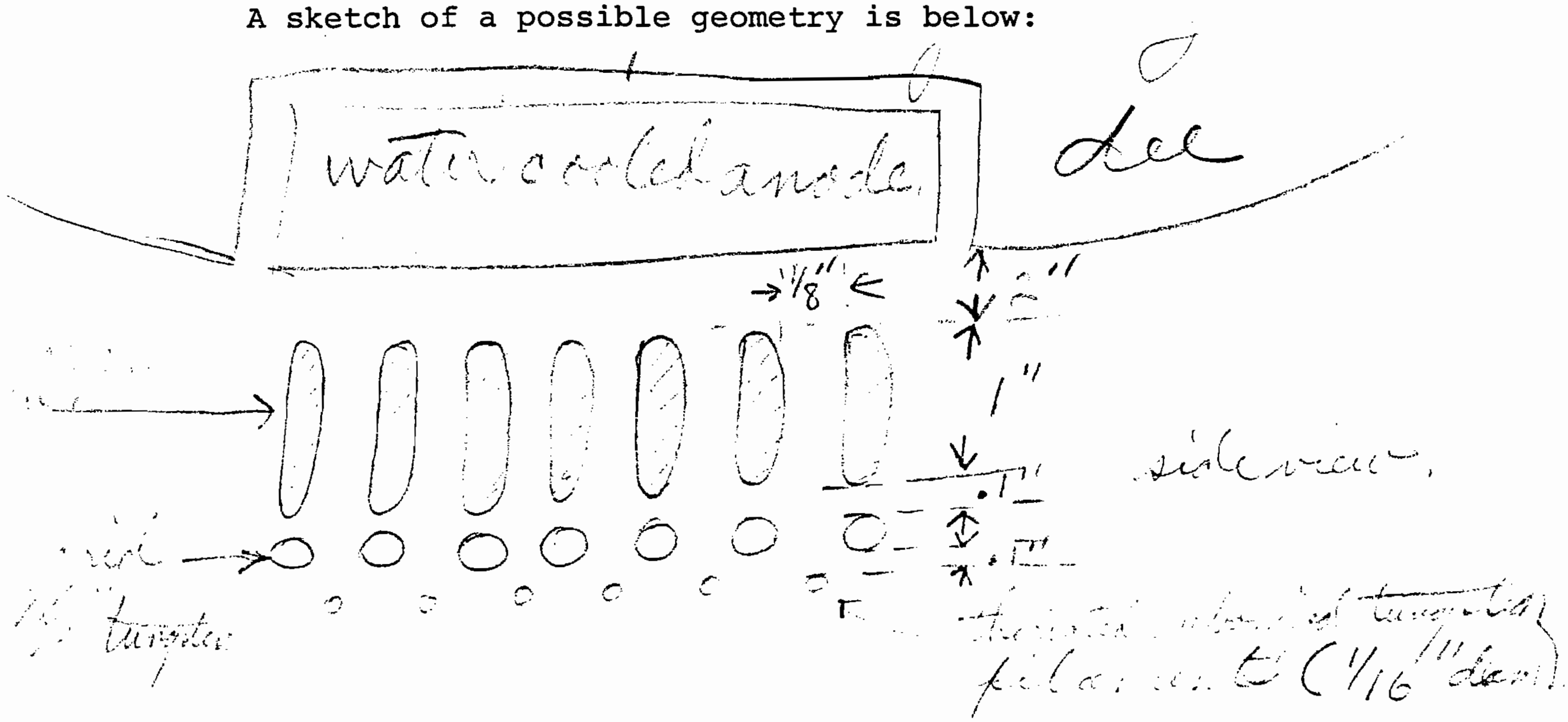
Even back in 1950 on the occasion of improving the 184 inch synchrocyclotron I strongly considered building the tube in the dee! There we only needed 20 KV rf and were prepared to bias the dee to 10KV. Why not bias it to 20KV and provide a cathode and grid at ground potential as in any vacuum tube and let the dee be the anode! I went so far as to build a filament and grid and tested it. It worked fine. But prudence said: use conventional means unless you can't! So we wound up using a 100 KW grounded grid self excited triode. It worked--in fact it is still working.

Now here at MSU we are tempted to again propose building the tube in the dee! With our MSUDS insulator design the dee can easily run with 200 KV rf+ a superposed 220KV+dc, and therefore makes a fine anode. Of course we would have to build a blocking condenser below the insulator, and no doubt there will be some problems with the cryogenic pumping lines and the beam pickups. If these problems loom too large we have two alternatives. Only a small (20 cm^2) area under the dee need be the anode and a blocker on only a few pfs is necessary between it and the dee. A dc cable through the stem can supply the power, and water cooling can remove the 100KW of power.

So now, under the dee we need only an emitting filament, a control grid and a screen grid. Advantage can be taken of the magnetic field so that very high transconductance can be achieved, with good shielding of the feedback capacity and no electrons should be intercepted by the grids. To minimize feedback capacity, we will probably use a pentode or even hexodide construction, so that practically no electrical field lines will go from the anode to the grid.

The second alternative is to leave the anode at ground and build the cathode grid, screen etc. floating at -- 220 KV. Although not appealing, principally because of the difficulty of making the cathode by pass condenser and supplying filament power, this method is nevertheless feasible.

A sketch of a possible geometry is below:



The screen would be solidly grounded and the cathode bypassed (100pf). So we would have to feed dc to the cathode and grid, rf drive to the grid, and heat the filament with about 20 KHz power. (5KW). In my prime, with the aid of a good accelerator technician and a convenient shop I could do this in a year.

At MSU there are people who would consider it trivial to calculate the electron trajectories in the presence of the vertical magnetic field, and they could also calculate exactly the feedback capacity, the transconductance, and the fraction of current intercepted by the grid and screen, and thus come up with a good design. I highly recommend that this approach be seriously considered, studied and executed, as it gets rid of all mode problems which otherwise will continuously vex us.

Electron Beam Transmitter

Another way to power the dee of a cyclotron to V volts peak is to inject an electron beam of energy $V+V^1$volts, where V^1 need only be 5 to 10 KV. If W is the power necessary to excite the dee to V volts, then $Rx = V^2/2W$ and the rms component of the chopped injected electron beam needs to be I= 2W/V. Effeciency will not be significantly impared if the current is on for 20^o out of each 360^o cycle. Thus, at 30 MHz, the electron beam would consist of 2 ns wide pulses. These pulses could look like a Gaussian, whose area is the same as the 2 ns pulses. A conventional tetrode tube produces pulses of electrons like this when operating class C and employing sine wave drive. The elements of the electron beam transmitter consist of a negative high voltage stand (voltage $V+V^1$), a cathode, a chopper, an accelerating column, a beam guide channel to the dee, and a water cooled anode in the dee. We will now describe what these might look like.

Anode in dee

Although it is possible to use a superconducting channel to exclude the cyclotron magnets field from the electron beam path, this probably isn't necessary, in fact, the vertical magnetic field is an excellent focusing field for the beam. The power delivered to the anode may be as much as 50 KW. A properly cooled surface can transfer 5 KW/cm^2 to water, so we need a minimum area of 10 cc. But 5KW is pushing it, so it seems reasonable to design for 20 cc. This means that the emittance of the source must be fairly large, in fact, it means that the cathode must have an area of at least 20cc.

Beam Guide Channel

It is visualized that this would be a hole through the valley pole, similar to our present feeder hole (3 1/2 inch). Perhaps it will have to be curved, to follow the field lines. Perhaps correction guide coils will be needed. If neither of these solutions is practical, then we will have to use a superconducting channel. Outside the pole we can use normal beam line techniques. The peak beam currents are on the order of 10 to 20 amps so strong focusing back to the source will probably be necessary.

Accelerating Column

Because of the space charge problem between the cathode and the end of the accelerating column, the column will be made reentrant into the high voltage cage and kept as short as possible. Five, or six forced potential rings on a column about 20 inches long overall seem reasonable. It is assumed that the power supply is a Cockroft Walton type divided into a maximum of 25 KV per deck, thus requiring 8 to 10 decks. These decks will provide the voltages for the gradient rings on the column.

Chopper + Cathode

It is presumed that we have a cathode, control grid, and screen grid of planar construction and possibly including a solenoidal magnetic field. With a 20 cm square cathode we need only about 1 amp per cc of emission, no problem for a thoriated carburized tungsten cathode.