MSU SCC RF SYSTEM

Note # 2 by J. Riedel 10/8/76

Coupling the transmitter to the dees

1. Statement of the Problem

The three dees of the Michigan State University superconducting cyclotron are to be connected mechanically and electrically together in the central region and a single transmitter is to supply the 150KW of rf power over a possible frequency range of 10 to 80 mHz. Besides the usual problems of supplying rf power to a vacuum high Q resonator over a very large frequency range the super conducting cyclotron provides very very limited access to the dees. There are only three possibilities: via a dee stem, via a 1 inch hole in the median plane which penetrates the cryogenically cooled magnet coil housing, ~~as~~ or via one or more 1½ inch holes in the pole faces near the outer radius of the dees. It is possible, at considerable expense to bore out these holes to 3" diam.

2. Loop coupling with a line in a stem

A very appealing way from an rf engineers viewpoint is to use an automatically variable loop coupled into one dee stem, the 50 ohm line passing through a hole near the outer radius of the moving short circuit anulus. The inner conductor could be 1" diam, large enough to allow for good water cooling, so that the line need not be used efficiently. This means that the dees need not terminate the line, resulting in being able to tie the transmitter end of the line directly to the anode of the tube (thru a blocking condenser, of course). Thus the line has a high standing wave ratio (~15/1) and acts as a coupled resonant element. Therefore it must be tuned, that is, it must be electrically $N\lambda/2$ long for any operating frequency. N can change over the operating frequency, in fact it is visualized as changing from 2 to 1.

The advantages of driving the dees this way are that first only the tube tuning inductance and the line length need be adjusted for each frequency, but since the coupling to the large circulating energy in the dees is strong, the accuracy of tuning need be only about ½%. But the main advantage is that the entire system is now well behaved under sparking, multipactoring or mistuning conditions. The voltages in the line and at the tube can never exceed the anode plate voltage. It also means that reactive energy can easily be transported back and forth across this line and that ultra fine tuning can be accomplished at the tube site, and that the criteria for tuning is a ~~contd~~ look up table for the stem shorts and tube inductor, and a phase detector between the tube's anode and grid to control the fine tuning of the dees. No monitoring of dee voltage is necessary; the constancy of the anode plate r f voltage being a sufficient criteria for amplitude regulations since the voltage ratios are constant.

However appealing the above driving scheme is it has two drawbacks. The length adjustment of the line is messy, but even worse, the hole in the moving short anulus compromises an already difficult design for this item.

It seems that the anulus would have to have a slice taken out of it for the feed line to be able to be close to the outer conductor of the stem, thus causing current concentration (double the average) on the nearest contact fingers. Since the current density on these fingers is already dangerously high for the average current, one is forced to look to another method of coupling the transmitter to the dees.

3. Using the median plane entrance

Since, after creating a channel thru the cryogenically coil housing, with the necessary insulation around the outer conductor, the hole will only be 1" or less, only desparation and the lack of any other entrance would result in choosing this method. But since a better way exists, namely, to use ~~the~~ one of the six holes in the magnet pole face, we will spend no more time on it.

4. Capacitive coupling thru one of ~~the~~ ~~six~~ twelve holes.

It is possible to enlarge the 12 holes (only 6 would have to be enlarged) so that a 3" inside diameter outer transmission line could be used to provide capacitive coupling to the dees. With this large d transmission line one could again work with a high standing wave ratio on the line, coupling directly to the tube anode and adjusting the line length to be $N\lambda/2$ long. However, with this weak capacitive coupling, ~~and~~ especially with the liklihood of a spark across the coupling capacitor, high voltages could still be induced into it, thus eliminating one of the principal virtues of this method of powering the dees. Besides, it is expensive to enlarge the holes.

So we are reduced to driving the dees in the conventional manner of using a line coupled in such a manner that the dees terminate it.

We consider the following circuit

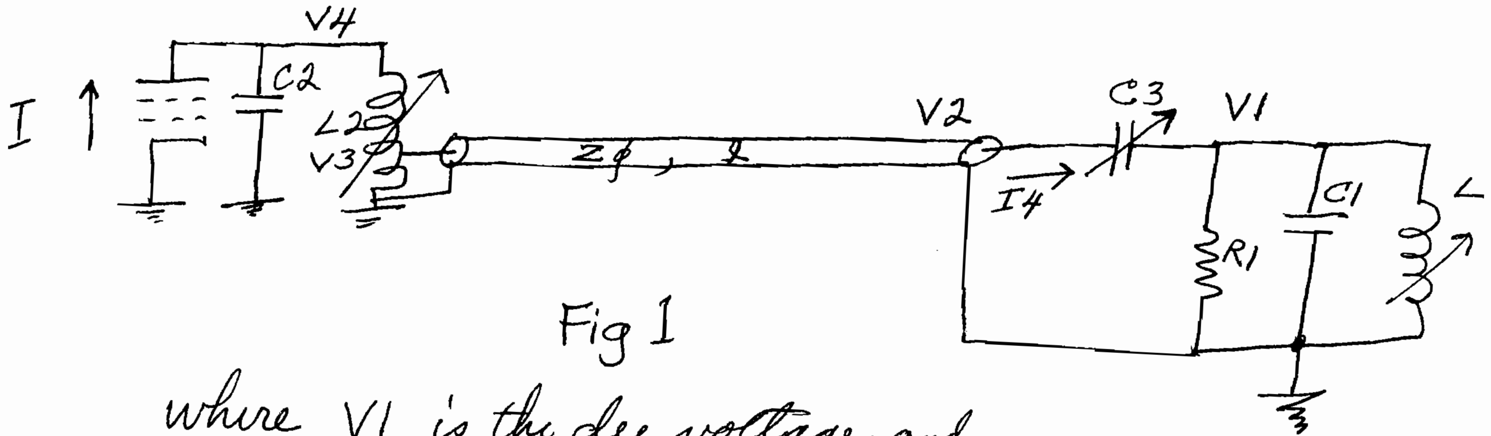


Fig 1

where V1 is the dee voltage and
L1, C1, R1 are the equivalent lumped elements of the dee + stem. From note 1 we assign $V1 = 10^5$ peak, W = 150 KW and Q = 5000 and calculate, for 20 mHz:

$L1 = 7.95775 \times 10^{-8}$

$C1 = 7.95775 \times 10^{-10}$

$R1 = 5 \times 10^4$

and if the resonator terminates the line thru C3

$I4 = \sqrt{W/Z_0} = 54.77$ amps (rms) and

$C3 = \dfrac{I4}{\omega(V1 - V2)} \approx 6\,pf$

$V2 = 2.7\,KV$

and if $F\phi$ is the resonant freq of L1, C1 the proper frequency for operation is pulled downward by 60 KHz.

The criterion for proper tune is that the phase of V1 leads the phase of V2 by 90°, and there is no reflected power in the line.

To match the line to the output impedance of the tube (300 Ω – 600 Ω) the line is tapped onto the inductance L2 required to resonate the tube capacity C2.

L2 is a transmission line greatly resembling ~~th~~ a dee stem, and is varied in the same manner, i.e., with a moving short. Here the diameters can be large enough such that the feeder end can penetrate through a hole in the anulus and thus the impedance matching can be automatically achieved over the entire frequency range. So to tune the rf system over the required range it is necessary to move only L1, C3 and L2. The tuning criteria for proper adjustment is

1. for L1 → phase of V1 is 90° leading V2
2. for C3 → no reflected power in the line
3. for L2 → V4 in phase with tube current, which means V4 in phase with grid drive voltage.

The line losses will be <u>285 watts/meter</u>.
It will be necessary to make or buy directional couplers for the line. This is no problem.

<u>Analysis</u> The performance of the above circuit has been computed on a computer over a large frequency range. Below Fø-10 KHz the impedance at the load end of the line is capacitive, is 50 Ω at Fø-10 KHz, is inductive from there to Fø where it is real (50,000 Ω) or = R1. Thus the line is basically open at Fø. above Fø the impedance is again capacitive. Far off resonance on either side, one sees C3 (> 3000 Ω) so again the line is basically open. The consequence of this is that it is possible to have very high voltages in the line when tuning up off resonance.

depending on the length of the line and the frequency. If, due to a spark, or due to multipactoring, the impedance of the dee is very low, again the voltages in the line can be very high, and also, depending on the line length, very little power can be fed into the dee. Since, in order to break thru the critical multipactoring voltages (about 100 volts) it is necessary to turn on with a high dV/dt, it is necessary to be at least within 1 part in Q of correct tune when turning on. This means that the instrumentation associated with measuring the criteria for adjusting L1, L2 and C3 ~~we~~ must be able to work over a 1000 to 1 amplitude range, so that the adjustments can be made with only 100 volts on the dees prior to turning on full drive. It also means that the change in tuning due to temperature should be less than .02%. This means very good water cooling on the dee stems.

After the transmission line has come out of the 1½" hole in the magnet the dimensions should be tapered to a standard 6" line and the inner conductor pass through a vacuum insulator to air. Then every meter or so from this point to the transmitter, which now can be well outside the shielding, one should place voltage monitors and protective spark gaps. If the line is of the order of 6 meters long then we can display the line voltage on six panel meters and instead of using the directional coupler to ~~tune~~ adjust C3 one can simply adjust C3 to make all these meters read the same, a sufficient criteria for no reflected power.

5. The terminated feed line

With a 1½ inch hole in the magnet it should be possible to have a water cooled outer conductor for the transmission line whose inner diameter is 1 inch. If the line is to be 50 ohms then the inner conductor should be .43 inches O.D. This conductor should be 1/32" wall thickness SS, copper plated. Thus we are left with a .37 inch hole for removing the 300 watts of heat generated in the vacuum portion of the inner conductor. One way of doing this is to use a thin wall 1/4" O.D. tube inside this hole to provide a reentrant water path, the other is to use gravity and the latent heat of evaporation of a suitable material (freon) and have the feed line penetrate the top of the magnet, the gaseous freon removing the heat via a heat exchanger where it condenses and falls back down to the bottom of the line to be reevaporated. In any case it seems that there is no great problem in removing this heat.

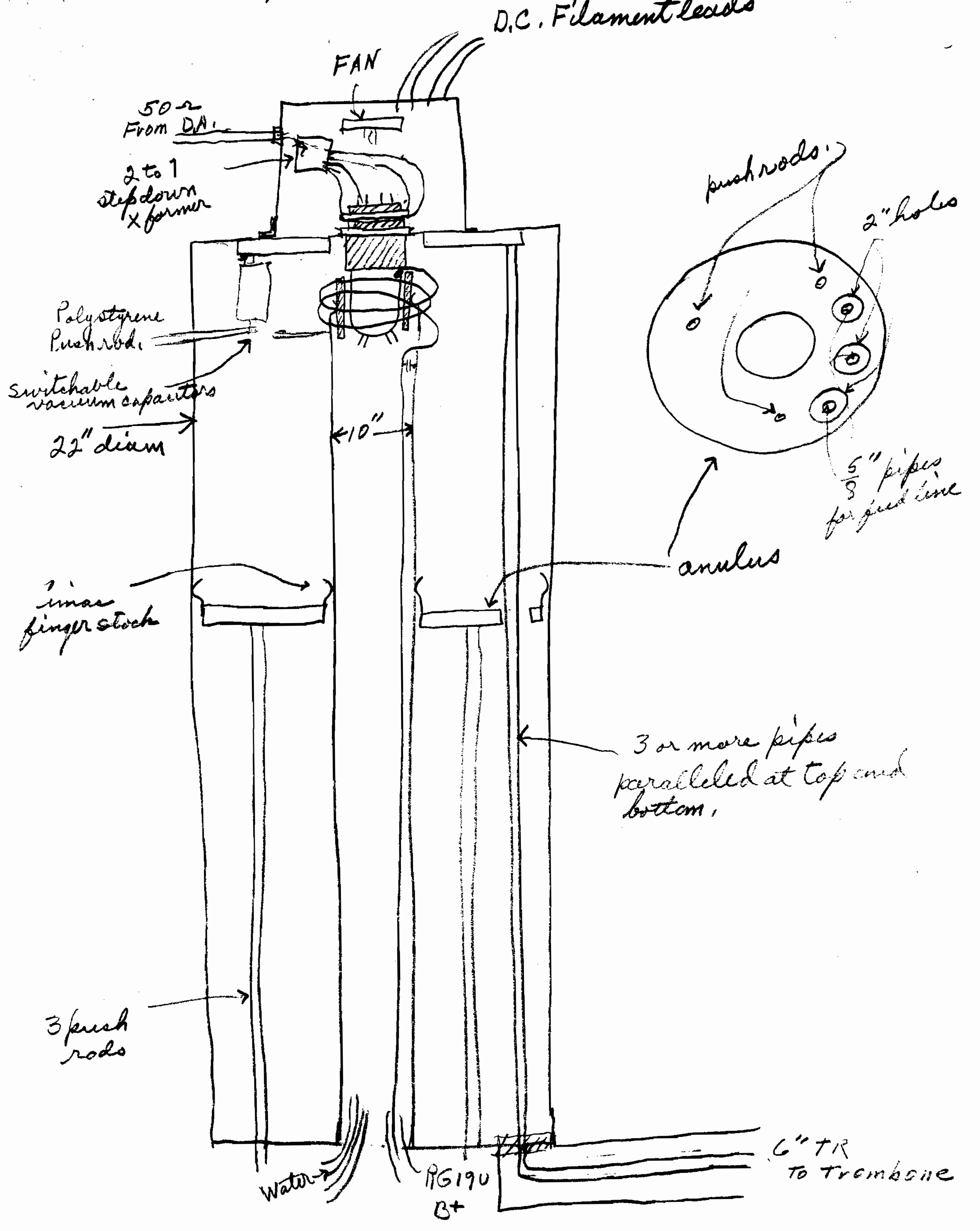
It is presumed that the six inch air line will penetrate the radiation shield so that the transmitter is accessible during operation. This means the total length will be ten to twenty feet, and there will be certain frequencies where the length will be an odd multiple of $\lambda/4$. It is believed this condition should be avoided so it is recommended that a trombone section should be added to the line to permit a length change of 4 feet. This is 30° at 20 mHz and should be sufficient to insure that under multipactoring, sparking, or mistuning conditions disaster does not threaten.

6. The transmitter. Fig 2 shows a sketch of a possible transmitter. Frequency tuning is accomplished by varying the position of the moving short circuit. 6 feet seems like a reasonable travel span for this, and to achieve tuning down to 20 or even 10 mHz, vacuum capacitors can be switched in at the anode, as shown. The feed lines which penetrates holes in the anulus are positioned to pick up about 1/3 the anode voltage

and be about 50 ohms. 50±20 is OK for the impedance of this section, because a little reflection here wont matter. Also the fraction of the anode voltage induced can vary by 30%, as the tubes output impedance can easily be adjusted over a large range by changing the drive, grid bias, or screen voltage.

It is presumed that the grid will be driven at 12.5 ohms ~~f~~ m derived from a distributed amplifier remotely located, as is being done at the 88 inch cyclotron, and recently, at ORIC. This DA can be built for about $5000. Because ~~the~~ our top frequency is 3 ~~th~~ times higher than at these other installations we may have to include a variable inductor in the grid, or go to a lower drive impedance. When I have the data sheets for the 4CW100000 I will study this problem.

FIG 2


D.C. Filament leads
FAN
50 Ω From D.A.
2 to 1 stepdown Xformer
Polystyrene Pushrod.
switchable vacuum capacitors
22" diam
10"
pushrods.
2" holes
5/8" pipes for feed line
anulus
inner finger stock
3 or more pipes paralleled at top and bottom.
3 push rods
Water
RG19U
B+
6" TR to Trombone