

MSU SCC RF System

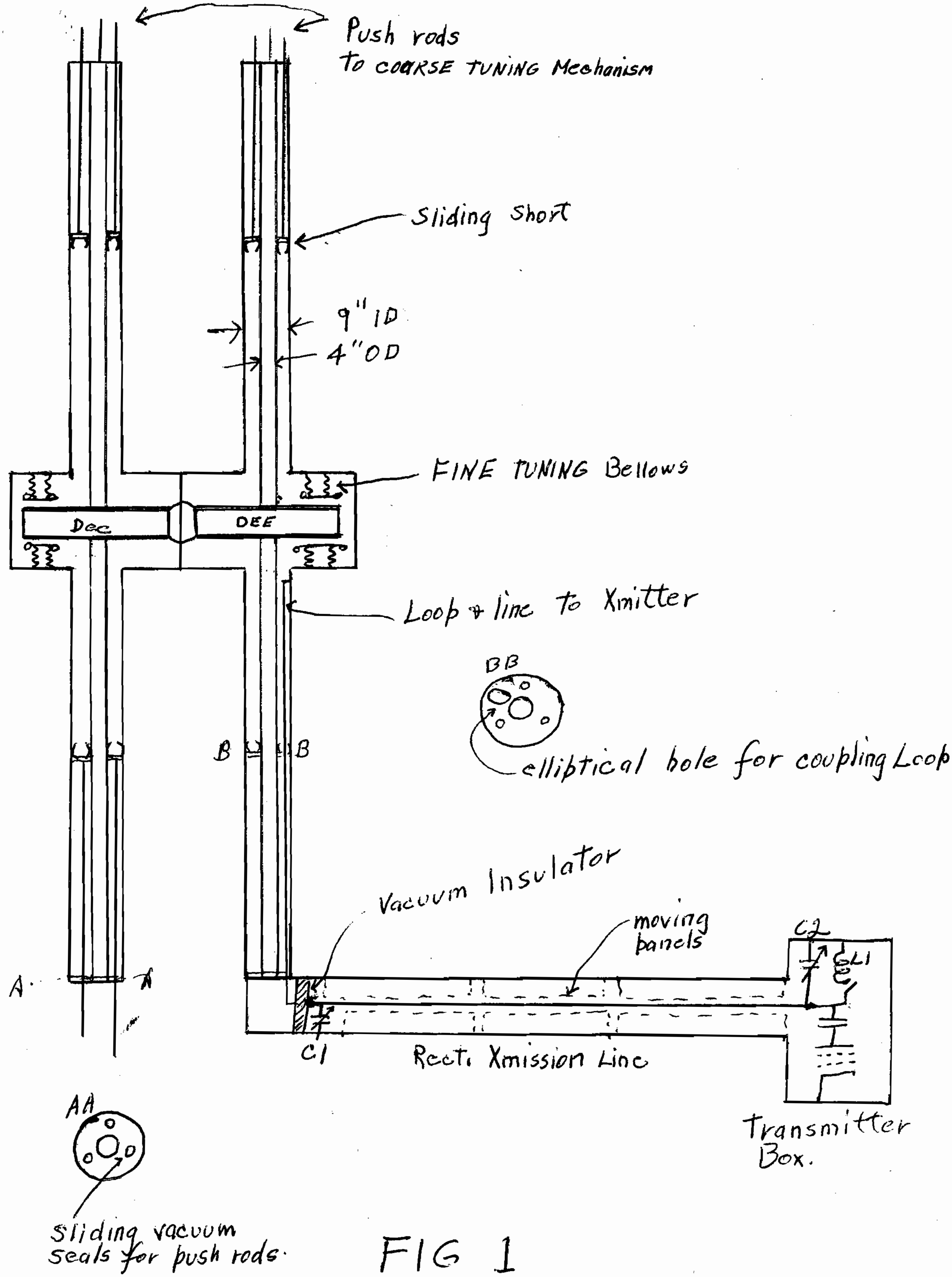
Note #1 by J. Riedel

Introd. The purpose of this note is to describe an rf system for the Michigan State University Superconducting Cyclotron that might work, make zeroeth order calculations of the power requirements and tuning mechanisms, describe a possible driving scheme, and submit a cost estimate for building it.

The specifications, in brief, are:

Dee voltage → 100 KV peak
3 dees, tied together at the center, and operating in phase over the frequency range 26.7 to 80 MHz. Minimum gap spacing perpendicular to the magnetic field = 1 cm.
Figure 1 shows two dees in a cross section where the spiralled dees are stretched straight. Also shown is the provision for coarse and fine tuning and connection to a transmitter via one of the dee stem coupling loops

This rf system will, of necessity, be very complicated. The main reasons are the large frequency range and the requirement that access and connections to the dees be only through the 10 inch diameter holes drilled through the magnet valleys and yokes.



Push rods
to COARSE TUNING Mechanism
Sliding short
9" ID
4" OD
FINE TUNING Bellows
Dee
DEE
Loop + line to Xmitter
BB
elliptical hole for coupling Loop
B
B
Vacuum Insulator
moving panels
C2
L1
A
A
C1
Rect. Xmission Line
Transmitter Box.
AA
sliding vacuum seals for push rods.

FIG 1

The dees are thus supported on 4" diameter pipes about 8 ft long and for mechanical rigidity considerations are connected together at the center. It might be possible to employ only the three lower stems as, since most of the r f energy is stored in the support lines (stems) the frequencies are almost the same with 3 stems as with 6 and the power will be almost one half. However there are two important reasons for using 6 stems: since it is about an electrical half wave length from the bottom center to the top center radially inward or outward there will be a large vertical component of voltage within the dee at the top frequency (perhaps 30 to 50 % of the accelerating voltage), and secondly the current flowing on the liner top to bottom connection in the center (about 250 amps) will cause a heating problem due to the necessarily small area of these connections. Without these connections all the current to charge the dee tops would have to come from the outer radius liner connections, resulting in an even larger vertical internal dee voltage.

R.F. Power requirements.

A. Scaling laws. If one has a capacitor which must be excited to a voltage V_ϕ at a frequency F1 and one uses a transmission line of outer and inner radii r2 and r1 to resonate it, then the power is independent of the value of the capacitor for capacity reactance values greater than .5 Z_ϕ where Z_ϕ is the line impedance. As the frequency is increased to F2 by shortening the line the power would decrease linearly with F if the r.f. ~~resistance~~ resistivity stayed constant, but since $R_{(RF)}$ varies as $\sqrt{F}$, then the power to excite the capacity varies as $\sqrt{F1/F2}$.

B. As for a first order calculation of the power requirements for the MSU SCC it is sufficient to calculate the power necessary to excite a $\lambda/4$ long line with no capacity loading.

$$Z_\phi = 138 \log(r1/r2) = 48.6 \text{ ohms}$$

$$R_\phi = 2.63 \times 10^{-7} \sqrt{F} \left(\frac{r2+r1}{r2 r1}\right) = 6 \times 10^{-3}\ \Omega/\text{meter}$$
at 26.7 mHz.

also

$$R'_\phi = \frac{1.26}{\sqrt{F}}\left(\frac{r1+r2}{r1 r2}\right) \text{ ohms/radian}$$

The current at the short will be

$$I_\phi = V_\phi / Z_o = 1450 \text{ amps rms}$$

and the power will be

$$W = R'_o I_\phi^2 \int_0^{\pi/2} \cos^2\theta \, d\theta = .63 \frac{r1+r2}{r1 r2} \frac{I_o^2}{\sqrt{F}}$$

at 26.7 mHz this is 25 K.W.

The circulating energy is

$$E = \frac{V_o^2}{Z_o} \int_0^{\pi/2} \sin^2\theta \, d\theta = \frac{V_o^2}{2 Z_o} = 10^8 \text{ VA}$$

and the circuit Q at 26.7 mHz $=$ 4000

So for 6 lines the power will be 150 KW. In practice the actual power always turns out to be from 10 to 20% higher than the exact calculations call for, so that for design purposes we should choose a figure of 180 KW. and assuming 60% plate efficiency in the transmitter, the power supply should be rated at 300 KW

Coarse Tuning

Coarse tuning is to be accomplished with ~~an an~~ anuluses which electrically short the inner and outer conductors of the stems together. ~~Tu~~ The maximum current, which will be at 80 MHz due to the effect of the lumped dee capacity, will be about 2000 amps resulting in a linear current density of 63 amps/cm on the inner conductor contacts. Since conventional sliding contacts with low pressure (< 10 lb/in^2) in vacuo are not considered reliable above a current density of 45 amps/cm these contacts will have to be better than any now being used in cyclotrons. It is believed that it is possible to ~~do~~ build hydraulically pressurized contactors with surface pressures of 12000 lb/in^2 that will be satisfactory. The contacts, of course only change position when the pressure is zero, so no wear takes place, and ~~the~~ 12000 psi is sufficient to break through copper oxide surface films, while not sufficiently large to cause inelastic distortion of the surface.

Computer or manual control should, after test data is fed into it, permit one to mechanically set the position ~~to within~~ ~~0.5% of the~~ so that the resonant frequency of each dee + stem is within ± .25% of the desired frequency. ~~Tol~~ This means ±.2 inches positioning.

It seems obvious that very soon in the preliminary design stage ~~an~~ a full current r f test should be made of the proposed design of these "sliding shorts, in vacuum, of course.

~~It is proposed that except for the one stem~~

It is proposed that these sliding shorts also make a fairly good vacuum seal, so that differential pumping on the bottom will permit one to tolerate pressures of the order of 10^{-6} torr in the vicinity of conventional neoprene ~~sealed~~ sliding seals for the three push rods. Also this ~~permits~~ allows for the possibility of sloppy push rod ~~joints~~ disconnectable joints, so that an extra 10 feet of vertical space top and bottom need not be provided for. Of course the hole in the one anulus necessary for the drive line clearance will still be a problem for the vacuum system.

Fine Tuning

It is proposed that fine tuning of ± .5% can very nicely be accomplished with one 4 inch diameter copper plated stainless steel bellows facing each dee half as shown in figure 1. These bellows, about 6 inches high and perhaps 3 flutes per inch have a wall thickness chosen so that at 1 atmosphere pressure they expand reversably by about .5 inches and the metal is still well below the elastic limit when the pressure is increased by another 2 atmospheres resulting in a 1 to 3 atm pressure variation causing a 1 inch ~~motion~~ variation in variable position. Setting the minimum dee to bellows top position at 1 inch, and increasing the top area to 20 in², the dee to bellows capacity will vary from 4.4 pf to 2.2 pf. or ± 1.1 pf.

at ~~80 mHz this results in $\frac{\Delta F}{F} = \pm$~~

and ~~at 26.7 the variation is ±~~

~~$\frac{\Delta F}{F} = 2\pi F Z_0 \Delta C$ for a λ/4 line~~

~~worst case is at 26.7 mHz where $\frac{\Delta F}{F} = \pm$~~

Now $\frac{\Delta F}{F} = \frac{\Delta P}{P} = \frac{V_0^2 \times 2\pi F \Delta C}{\frac{V_0^2}{Z_0}} = 2\pi F \Delta C Z_0$

worst case is at 26.7 mHz where $\frac{\Delta F}{F} = \pm 9 \times 10^{-3} \approx \pm 1\%$ obviously quite adequate, and consistent with the specification for the coarse tuning.

The mechanical resonance frequency of these bellows when loaded with a pressurized liquid (for cooling and control) will probably be less than

10 Hz, but well damped due to the circulating fluid and magnetic field. Even so this means that unity gain in the frequency control will be less than 5 Hz, which may be satisfactory since it is better than any other cyclotron except Princetons ($F_{unity\ gain} = 10\ Hz$). If not, we can add .005% additional control with ferrites coupled into the transmitting tube, with possibilities of unity gain frequency control up to 10 KHz.

Driving Scheme

All six stems can be driven from one loop. This loop is really a transmission line coupling into one of the stems. It is envisioned as a 3/4 inch diameter pipe supported by a rigid connection to the liner at the top and by an insulator at the bottom of the 7 or 8 ft span. Its radial position between the inner and outer conductor of the stem line will probably vary with height to couple the correct flux, thus the hole in the moving anulus must be an ellipse. At the insulator the length is already greater than $\lambda/2$ at 80 mHz, so there is no way of avoiding continuing the line and making the total length to the tube be λ long (about 150 inches, or 12.5 ft). The tube capacity will be resonated out at 80 mHz with an inductance L1. As the frequency is lowered proper impedance matching will be achieved by increasing C1 and C2, vacuum variables placed at the insulator and at the tube, and by changing the Z_o of the air part of the line (50") via moving panels in a rectangular line configuration. Below 65 MHz L1 is disconnected and C2 appropriately increased. At 53 MHz we change modes — from a λ to $\lambda/2$ electrically long. This will change the phase relationship between the dee and the transmitter by 180°, but this is a simple matter to compensate for in the low level stages of the rf system.

To set the parameters for this feeder system requires some time with an interactive iteration type program on a computer. Everything is completely amenable to exact calculations and no problems are envisioned. The standing wave ratio on this line will be about 20 to 1 with current maxima of about 300 amps rms and 14 KV rms at voltage maxima. Line losses will probably be about 2 KW.

Transmitter

It is proposed that the final tube will be a 4CW100000A and the circuit configuration be cascode, similar to that employed at FNAL. Actually, an exact copy of the FNAL transmitter would probably work fine. Since FNAL has many of these it probably is possible to acquire one of their spares entire and thus save a lot of $ and time. Perhaps the lossy ferrite between the 4CW800's and the cathode of the final would have to be slightly modified for operation at 80 mHz since their design was for only 50 mHz, but Q. Kerns would know about this. Also the screen bypass condenser arrangement probably needs modifying.

Power Supply: The power supply would be rated at 20KV, 15 amps with self contained crowbar.

Low level. The low level circuits for amplitude and phase regulation can be copies of systems employed on existing cyclotrons. However, instead, it would be desireable to do these right. Therefore it is proposed that the method engineered for the GANIL cyclotrons be used. The main difference is in the synthesizer which is required to be a little special. To permit frequency independent ~~phase~~ electronic phase shifters and phase detectors to be constructed, and to allow for the possibility of ~~ab ph~~ precision phase detection between two signals harmonically related requires that the synthesizer produce phase stable outputs in quadrature at F, 2F, 3F, 4F, 5F, 6F and ~~at F+~~ a single side ~~band of~~ F
F+, 2F+, 3F+, 4F+, 5F+, 6F+ where + means plus 5 MHz (single side band outputs).

There is a GANIL paper describing the reasons for wanting such a synthesizer and describing not only how to make this synthesizer but how to build the phase shifters and phase ~~shifters~~ detectors.

Cost estimate for the MSU superconducting cyclotron.

~~Power~~ Main Power Supply	$ 75,000
Cascode Transmitter from NAL with DA	10,000
auxilliary power supplies	16,000
NIM Bin + electronics	6,000
Power Controls	5,000
special synthesizer	6,000
total	$ 118,000
Engineering	10,000

Note above does not include labor, the feeder, the hydraulic system for fine tuning, or the mechanism for the moving short circuits.