Subject

COAXIAL TRANSMISSION LINE FOR THE NAL 200 MEV LINAC

SUMMARY: Manufacturers' ratings of several large rigid coaxial transmission lines are examined and compared to the experience of other laboratories using similar lines to transmit rf power to proton linac accelerating cavities. It is concluded that nominal 9" line should be adequate for the NAL 200 MeV linac.

1. In low-duty rf systems such as the linac will have, peak power is the principal parameter which one must consider in selecting a transmission line. The peak power limit is set by voltage breakdown.

2. The optimum impedance of an air-filled coaxial line for highest possible peak power transmission within a given outside diameter is 30 ohms, for which the ratio of outer conductor ID to inner conductor OD is 1.65 to 1. The common 50 ohm line, with conductor diameter ratio of 2.3 to 1, can transmit 86% as much power as the 30 ohm line of the same outside diameter. Since large coaxial lines are available commercially only in 50 and 75 ohm impedances, and 75 ohm lines will handle still less power, only 50 ohm systems are considered in the rest of this note.

3. Each manufacturer of such equipment lists a maximum recommended rf power level for each of his lines, assuming perfect termination of the line (VSWR=1.0). When the termination is imperfect, so that there are standing waves on the line, the power level transmitted should be reduced to keep the peak voltage level at any point in the line no higher than the recommended value. The high-potential test actually given the line parts on final inspection is typically about three times as high as the maximum recommended working voltage, giving comfortable margin to accomodate deterioration of insulators, unanticipated reflections, and so on. See Table I.

TABLE I

RATINGS OF COMMERCIAL RIGID COAXIAL LINES

Nominal size	Manufacturer and type	Test voltage DC or peak AC	Peak field on center conductor at test voltage	Recommended peak operating voltage	Recommended maximum power
3½"	Dielectric Products	39 kV	28.0 kV/cm	9.8 kV	0.96 MW
3½"	Andrew (standard)	19 kV	13.6 kV/cm	6.3 kV	0.40 MW
6½"	Dielectric Products	59 kV	21.4 kV/cm	17.3 kV	3.0 MW
6½"	Andrew (standard)	35 kV	12.7 kV/cm	12.2 kV	1.5 MW
6½"	Andrew (high-voltage)	50 kV	18.2 kV/cm	17.3 kV	3.0 MW
9-3/16"	Dielectric Products	72 kV	17.4 kV/cm	23.9 kV	5.7 MW
9"	Andrew (standard)	50 kV	12.4 kV/cm	17.3 kV	3.0 MW
9"	Andrew (high-voltage)	71 kV	17.6 kV/cm	24.5 kV	6.0 MW

Note that the voltage ratings of the lines in the table fall into a "low voltage" and a "high voltage" class. The Andrew standard lines are tested at voltages that correspond to peak fields of about 12-13 kV/cm; the Dielectric Products lines and the Andrew high-voltage lines are tested at voltages that correspond to peak fields of 17 kV/cm or more. The low-voltage lines use simple disc and peg insulators; the high voltage lines use insulators with surfaces that are contoured to give long creepage paths, and have center-conductor hardware with careful rounding of corners and other possible high-field regions.

4. When power is first applied to a high-Q resonant circuit, such as a linac accelerating cavity, the quasi-impedance it presents to the driving system is very different from that which it presents after the turn-on transient has died out. (While impedance is, strictly, a steady-state concept, one may usefully think of the ratio of voltage to current at the drive point as being impedance-like as long as the Q is high enough so that it takes very many cycles to turn the system on, and the change from cycle to cycle is small.)

5. In our case, in which loop coupling will be used, the loop will look like a low impedance - essentially its own inductive reactance - at turn-on. Then, as the stored energy in the cavity builds up, more and more magnetic flux from the cavity currents will begin to link the loop and the loop will present a growing impedance to the transmission line, finally reaching a match at steady state. (In practice we shall probably choose the matched state to be one with 75 milliamperes of beam loading the cavity.) This means that the VSWR will be very high at the beginning of the pulse. On the other hand, the power being transmitted then will be relatively low, because the final amplifier will see a bad mismatch and cannot generate much output power.

6. The high VSWR will tend to produce high voltage maxima on the line. The low output power from the tube will tend to reduce them. If these two effects approximately cancel out, we can work our transmission line up to the manufacturer's recommended power

levels. If they do not, we must be more conservative. In judging the situation, it is helpful to consider the experience of other laboratories who drive comparable proton linac cavities.

7. Experience at the Rutherford Laboratory PLA: For several years, nominal 3" line was used at power levels of the order of 1.4 MW feeding the second and third accelerating cavities. The system was marginal, and breakdowns occurred too frequently. "The main faults were found to be due to garter spring connections, finger strips, and soft-soldered joints.... Bellows type flexible sections of coaxial line are also troublesome and are being replaced." (From the 1962 PLA progress report, pp 5-6.) Modifications were then made, and "All the R.F. at peak power of 1 MW and over is now transmitted through 4 1/2" coaxial line." (From the 1963 PLA progress report, p 6.)

8. We do not have details of the 3" and 4 1/2" lines used, but if they were built with simple disc insulators the 3" line should be comparable to the Andrews 3 1/8" (which the manufacturer rates for 0.4 MW maximum power) and the 4½" line should be rated at $(0.4)(4.5/3.0)^2=0.9$ MW on the same basis.

9. Experience at the Brookhaven AGS: For the past two years, a short length of 8" coaxial line has been used to transmit more than 4 MW of power to the 50 MeV accelerating cavity there The center conductor was supported at the tank end by a 2" thick straight-sided disc of Teflon which served as the vacuum window; at the other end it was supported by a shorting stub, so that no insulator was needed there. There was recurrent difficulty with breakdown of the line across the air side of the vacuum window; the breakdown sometimes occurred when r-f was first turned on, sometimes at the time that the step to a higher modulator voltage was made (to compensate for beam loading). In October 1968 a major modification in the rf system was made: the tank is now driven by three TH-515 triodes each feeding a separate loop through 8" coax.

10. An 8" 50-ohm line made with simple disc insulators may be compared to both the Andrew 6 1/8" standard line, which the manufacturer rates for 1.5 MW maximum power, and the Andrew 9" standard line, which the manufacturer rates for 3.0 MW maximum power. Estimating a nominal rating for the 8" line gives us: $(1.5)(8/6.125)^2=2.6$ MW, and $(3.0)(9/8)^2=2.4$ MW. An average value of 2.5 MW would be reasonable.

11. The Brookhaven line is less than two feet long, so short that end effects prevent one from making good measurements of reflected power. One expects a voltage minimum at the loop during turn-on; the vacuum window was located within a few inches of the loop, and therefore should have been at a relatively low-voltage point, yet breakdown occurred there. The system operated satisfactorily, but only when the tank was slightly detuned to give a more favorable voltage pattern on the line.

12. Brookhaven now plans to use a 12" coaxial line to transmit power to the accelerating cavities of their 200 MeV linac. If this line, like the Brookhaven 8" line, does not use contouring of the insulator surfaces to increase the creepage paths, its nominal power rating extrapolated from the Andrew 9" line should be: $(3.0)(12/9)^2=5.3$ MW. If Brookhaven is, like us, designing for 75 ma of beam, the maximum power to any cavity should not exceed 4.8 MW; if their design is (as has been rumored) intended to be safe for as much as 200 ma of beam, the maximum power may be as much as 7.4 MW.

13. If the above data are correct, it now appears that other laboratories driving proton linac cavities are accustomed to use non-pressurized rigid coaxial line at power levels above what we would expect a manufacturer would recommend for such lines: Rutherford was using a nominal 0.4 MW line at well above 1 MW and found it marginally useful, and are now using a nominal 0.9 MW line successfully.

Brookhaven could use a nominal 2.4 MW line at more than 4 MW when tuning was modified to give a favorable standing-wave pattern, and may be planning to use a nominal 5.3 MW line at powers as high as 7.4 MW.

14. One may tentatively conclude that a line rated by its manufacturer to transmit our design power should be satisfactory for use in driving a high-Q linac cavity, in spite of the fact that there will be a bad mismatch on the line at the start of each rf pulse. In this case, since we wish to transmit a maximum of 5 MW of power, either the Dielectric Products 9-3/16" line, rated at 5.7 MW, or the Andrew high-voltage 9" line, rated at 6.0 MW should be suitable.

15. Because the data in paragraphs 7 though 12 above are too fragmentary for positive assurance that they are really applicable in all respects to our case, one should provide a safety margin. This is conveniently available in pressurization of the line. All of the lines discussed above were used (and rated) at normal atmospheric pressure. The transmission line manufacturers both state that pressurizing their lines to 30 psi (2 atmospheres) absolute with dry air will increase their power-handling capability by more than a factor of 2, and the same pressure of SF_6 will increase their capability by about 16 times. All of their lines and fittings are commonly used at this pressure, and often are run as high as 60 psi absolute. It seems reasonable that we should design our system (especially including the vacuum window) in such a way that it can be pressurized to at least 2 atmospheres absolute.

.6. Note that suggesting, as I did in paragraphs 5 and 6 above, that the bad match seen by the final amplifier tube prevents it from delivering enough power to the line to produce excessive voltages even when the VSWR is large, assumes that the two-way travel time on the coaxial line is short compared to the rise time of the plate voltage pulse on the final amplifier. Obviously, before any reflections on the output line have had time to come back to the final amplifier it will see only a 50 ohm load, and if it reaches nearly rated output power with large reflections coming back from the tank coupling loop, brief voltage doubling will be observed at the voltage maxima along the line. To prevent trouble from this source, it should be sufficient to limit the 10-90% rise time of the plate modulator voltage to a few times the two-way travel time of the final amplifier output coaxial line.