DRIFT TUBE AND PARAMETER SELECTION FOR LINEAR ACCELERATOR STRUCTURES BELOW 150 MEV

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With three linac proposals being submitted to the USAEC this year, the question has arisen whether money could be saved by cooperation between the different groups. Savings could be realized in research and design, engineering, and in procuring similar items in greater quantities. Since each of these linacs have different basic design parameters such as the duty factor, beam current, energy, etc., the question arises whether a common design is really feasible. Certainly below 200 MeV where a drift tube loaded Alvarez structure is proposed there are many similarities. However, if one looks at the basic parameters which are to be met by each and tries to fit a common design to these parameters, one soon realizes that this is not possible. Wheeler has looked at this problem in detail[1] and concludes that if LASL agrees to derate their power supply so as to require an additional power module for the extra tank needed, which is the same as having the capability of accelerating a larger current but not doing so, and which of course would raise the cost of their proposal, then a common design is possible. If all three linacs were built, the saving in the common design might more than offset the added cost to LASL. I do not want to get too involved in this question. Rather I would like to point out that it is still possible to meet the basic parameters of each laboratory without adding greatly to fabrication costs if decisions can be reached on drift tube and tank structures which are fabricated of similar modules.

In order to reach agreement between the different laboratories on drift tube shapes, a committee was formed whose purpose was to try to enumerate the problem areas in adopting a particular drift tube shape and to try to expedite work in these areas. This committee made certain recommendations which I shall relate and work is proceeding in other areas. Since the committee was formed, its activities have been extended to a selection of parameters for the 200 Mc portion of the linac. If agreement can be reached, then savings should be realized in design and in larger volume purchases of similar components.

So far, the following recommendations have been made by the drift tube subcommittee:

1. Since sparking is mostly confined to the first gaps in operating linacs, it is desirable to design a short first section which can

be operated at reduced gradients. At 750 keV an average gap field of 8 MV/m or less should prevent excessive sparking for conventional shaped drift tubes. Above 10 MeV an average gap field of 12 to 13 MV/m is considered conservative.

2. An operating frequency of 201.25 Mc should allow design requirements to be met and give minimum interference with existing FCC allotted bands.

3. A drift tube hole of 2 cm has been achieved in the first drift tube at 0.75 MeV with a dc quadrupole and without unduly affecting the radial transit time factor. A linear increase from this size up to 4 cm at 200 MeV is recommended.

4. Satisfactory dc quadrupoles for drift tubes have been built and could be used in future design without major modifications.

5. A single drift tube stem is adequate even though a large diameter is required to accommodate four cooling leads.

6. The current computer programs for the calculation of drift tube shapes are sufficiently accurate so that extensive modelling is unnecessary.

7. Cylindrical shaped drift tubes at the higher energies can be chosen which are not far from an optimum shape and which, in addition, can be more easily fabricated.

In order to choose a drift tube shape, it is necessary to arrive at figures concerning the cost of rf power, the cost per unit length of the linac, the diameter of drift tubes which allow quadrupoles and adequate cooling, the maximum value of the accelerating rf gradients, the operating costs of the linac, as well as many other interacting requirements. In the months ahead many of these items will be better evaluated. To attempt to optimize the rf structure, including drift tube shape, clearly requires these considerations to be adequately assessed. However, even with the present knowledge it is instructive to understand the way these parameters affect the structure.

The total cost for building and operating a linac in terms of the power and length may be written as:

$$C = C_f + C_p P + C_{op} P t + C_L L + C_{oL} L t$$

where:

C_f = fixed costs
C_p = power costs per unit of power
C_{op} = power operating cost per unit of power per unit time
C_L = length costs per unit length
C_{oL} = length operating cost per unit length per unit time

A great deal of effort is being expended on an evaluation of the cost coefficients at the present time. The operating cost coefficients are difficult to assess, but after some searching through records of laboratories with operating linacs, we have found that if one takes t = 10 years, a possible lifetime of such a linac, then (within the error of determining these coefficients):

$$C_p \approx C_{op}\, t$$
$$C_L \approx C_{oL}\, t \;.$$

Now rewriting the formula in such a way as to give prominence to the factors which influence the structure

$$\frac{C - C_f}{2} = C_p\, P + C_L\, L$$

with the power P per energy gain ΔW given by

$$\frac{P}{\Delta W} = \frac{E_o\, T}{Z T^2 \cos \varphi}$$

and the length L per energy gain by

$$\frac{L}{\Delta W} = \frac{1}{E_o\, T \cos \varphi}$$

where E_o is the average peak axial accelerating field, T the longitudinal transit time factor, and φ the stable phase angle. In practice the power has to be increased, (a) to allow for losses on drift tube stems, tuners, and end plates as well as additional losses accounting for a lower Q value than the calculated value , and (b) reserve power to take care of beam loading. The power will be increased by a factor k to take care of the former, and a term $C_p\, I_B\, \Delta W$ added to allow for a beam I_B. With these considerations, the cost formula becomes:

$$\frac{C - C_f}{2} = \frac{C_p\, k\, E_o\, T\, \Delta W}{Z T^2 \cos \varphi} + C_p\, I_B\, \Delta W + C_L \frac{\Delta W}{E_o\, T \cos \varphi}$$

or

$$\frac{1}{\Delta W}\left[\frac{C - C_f}{2}\right] - C_p I_B = C_p\left[\frac{k E_o T}{Z T^2 \cos \varphi}\right] + C_L\left[\frac{1}{E_o T \cos \varphi}\right]$$

where the terms on the right are related to the choice of geometry. For any particular description of the geometry which specifes a value for Z and T, a cost can be calculated. The lowest cost will correspond to the largest value of Z and T. However, this alone does not allow one to choose a geometry that will allow the desired accelerating gradient to be achieved without excessive sparking. An accelerating gradient which will minimize this cost equation can be determined and is given by

$$E_o = \left[\frac{Z C_L}{k C_p}\right]^{1/2} .$$

This value of E_o is shown plotted in Fig. 1 as a function of Z. For any description of the geometry which gives a value of the shunt impedance Z, the value of E_o can be determined which gives a cost minimum. However before this information can be used in linac design, it is necessary to know what gradient can be maintained without problems due to sparking. Attempts are now being made to set safe sparking limits by accumulating data on operating linacs and by experimental measurements on a sparking cavity at this laboratory. Some preliminary results on the sparking cavity will be mentioned later. In the absence of a suitable explanation of sparking, one can use a value for the maximum field on the surface, such as the Kilpatrick criteria.[2] The MURA field computational program, MESSYMESH, can calculate the maximum value of the field on the surface of a drift tube. Actually what is calculated is a factor α, where

$$\alpha = \frac{E_{max}\text{ (on surface)}}{E_o} .$$

For some peak value on the surface, the value E_o can be calculated for the geometry considered. This value of E_o may be less than the optimum value of E_o obtained from the cost function for that particular geometry. If this is so, then to go to the optimum value would clearly cause maximum fields in excess of the chosen peak value on the surface and a danger of sparking. However, if it turns out that this value is greater than the optimum E_o, then sparking is not a problem because power is too expensive to go to the sparking level anyhow.

Using the MURA field computational program, we have investigated nearly 2000 different geometries for cylindrical shaped drift tubes. A large number of runs have been done at energies of 50, 100, 150, and 200 MeV. When these runs are evaluated using the cost formula, it is possible to choose an optimum set of parameters that describe the geometry. This optimizing procedure using a specified value of the maximum field on the surface was described at the Yale Linac Conference.[3] If each run is plotted on the Z, E_0 diagram with the value Z corresponding to the geometry and the value E_0 calculated on the basis of an upper limit for the maximum field on the surface, one can observe the importance of the sparking restriction. At 50 MeV the cluster of points lie to the left of the curve of optimum gradient; at 100 MeV the cluster of points lie closer to the curve; and as the energy increases, the cluster moves closer to the curve. At 50 MeV, clearly money can be saved by raising the gradient to more nearly approach the optimum. At the higher energies where the value of Z is lower, it is not as definite and depends on the diameter of the drift tube which may be specified from engineering considerations.

Any practical drift tube must allow space for quadrupoles and cooling. This places an additional restriction on the diameter of a drift tube. Our studies indicate that a diameter of 15 or 16 cm is necessary especially for a high duty factor linac at energies of about 200 MeV. The latest popular cost data indicate that this diameter is a departure from the cost minimum and that it is unwise from sparking considerations to raise the accelerating gradient to the optimum value. However, it should be pointed out that the cost minima are rather flat so that the departure from the minimum may not be a great penalty. When one considers raising the gradient to reduce cost, one must also consider the limitation on the power amplifier tube. A shorter linac with a greater multiplicity of tanks and power amplifier tubes, phasing systems, and poorer reliability may not be a suitable way to save money.

When the specifications of the 200 Mc linacs at the three laboratories are considered, it is found possible to arrive at a design which uses many similar components. In particular, it is possible to maintain a constant drift tube diameter from 50 or 60 MeV upwards. Thus cylindrical drift tubes could be fabricated out of stock material with similar end caps. Quadrupoles might also be alike. The tank diameters can be similar, although of different lengths. By mass procurement of these similar components or pieces overall cost reductions can be realized when two or more linacs are constructed simultaneously without the necessity of requiring a departure from the basic design parameters.

To gather more information on the sparking restriction we have fabricated a one unit-cell cavity, with movable end plates so that geometry from 5 MeV to 150 MeV can be investigated under full power conditions.

This cavity is driven by an RCA 2515E (2041) power amplifer capable of approximately 300 kW at pulse lengths of about 500 μsec and about 30 pulses per second, and at a frequency of 200 Mc. Our initial operation was at 50 MeV with a drift tube diameter of 16 cm, 3 cm hole, and 4 cm curvature on the outer corner (the cavity diameter is 79 cm). At the present time we have operated up to 125 kW in the cavity. This power level corresponds to an average accelerating gradient (E_o) of 2.7 MV/m, an average gap field of 10 MV/m, or a peak field on the surface of 16 MV/m. At this level there was not a single spark detected, it was just a matter of running the power up. We are now trying to get more power out of the power supply to go to a level where we can see a few sparks. However, the next step will be to go to 5 MeV where sparks should occur at a lower power level. Here hopefully we can study the phenomena.

WHEELER: This type of expression for cost, which both Don and I have used, leaves out a very important consideration especially for the injectors, that is, there is nothing in the equation which says anything about the reliability of the accelerator. The constant k, which comes from experience, can be used to contribute to the reliability and one should consider very seriously keeping k a fairly large number. Experience with most of the proton linacs to date certainly shows that they have been underpowered. By increasing k one can design for lots of reserve power and this of course will greatly improve the reliability. The other matter is the choice of E_o with respect to sparking limit. In the MURA sparking cavity I am told that the x-ray background at the 125 kW level is rising very rapidly and I would predict that, at 16 MV/m on the surface, you are very close to the sparking limit. We have observed in the heavy ion machine that the x-ray background rises very steeply just before the sparking level is reached. So again in terms of reliability for the machine, one should be very conservative in keeping the value of the maximum field safely below the sparking limit. These two factors are very important in terms of achieving highly reliable machines.

LEISS: People have been using cost formulas for years and have systematically left out what is really in many projects the biggest cost of all, that is the project salaries. Have you thought how to integrate some of this into guessing what is the best to do? This would be particularly advantageous, although difficult, if examining the desirability of a common design.

YOUNG: The rules are becoming clearer now on how you estimate cost, even the salary costs. MURA has a technical note on their experience on cost estimation and other people have discussed these things with the AEC to see how salaries should be integrated into the total project cost. This has not been put into the cost formula used here; this is a bigger operation research project than has been undertaken so far.

HUBBARD: As Wheeler pointed out, when you get somewhere near the sparking limit, you get a large amount of x-rays out of the machine which you must shield against. If you just lower the gradient slightly, the x-rays go down rapidly. Have you given any consideration to the amount of shielding necessary if you operate close to the sparking limit or have you put this into the cost formula?

YOUNG: We have not put the cost of shielding into the cost formula as a function of the gradient, only the cost of shielding as a part of the building costs which is part of the length costs. We intend, however, to make some measurements on the sparking cavity of the radiation background as a function of the voltage across the gap. We would like to get some good values for these quantities.

FEATHERSTONE: For the benefit of those of you who have not been paying close attention to the argument about sparking, I would just like to say a couple of words that I think should be repeated again and again. Mr. Kilpatrick wrote his "criterion", as it is so often referred to, in an attempt to integrate a great deal of data from many different sources and to account for it in an approximate way. I do not believe that he himself has ever given it the degree of authority that one would think it had by listening to the use of "Kilpatrick's criterion." Second, it was not intended as a working upper limit, but rather as a threshold level below which no sparking at all is expected to occur. Third, at 200 Mc a great many of the terms of his equation drop out and one arrives at something which is related only to the maximum field strength at the surface of the electrode. I think there is an accumulating body of evidence which indicates this is not adequate to account for the sparking we have observed in practical machines. I am very glad to hear Don say that they are going to try the spark cavity down in the equivalent of the 5 MeV energy region. What was the equivalent energy range of the present drift tube size?

YOUNG: 50 MeV.

FEATHERSTONE: The experience with the Brookhaven and Argonne linacs suggests strongly that something different is going on at the low energy end of the machine where there seem to be lower gradients and more sparking than at the high energy end. I don't think the gradient alone is enough to account for what we see. Of course, everybody knows that sparking is affected by surface conditions and vacuum quality, but we presume that the surface conditions and vacuum conditions are pretty uniform from end to end.

REFERENCES

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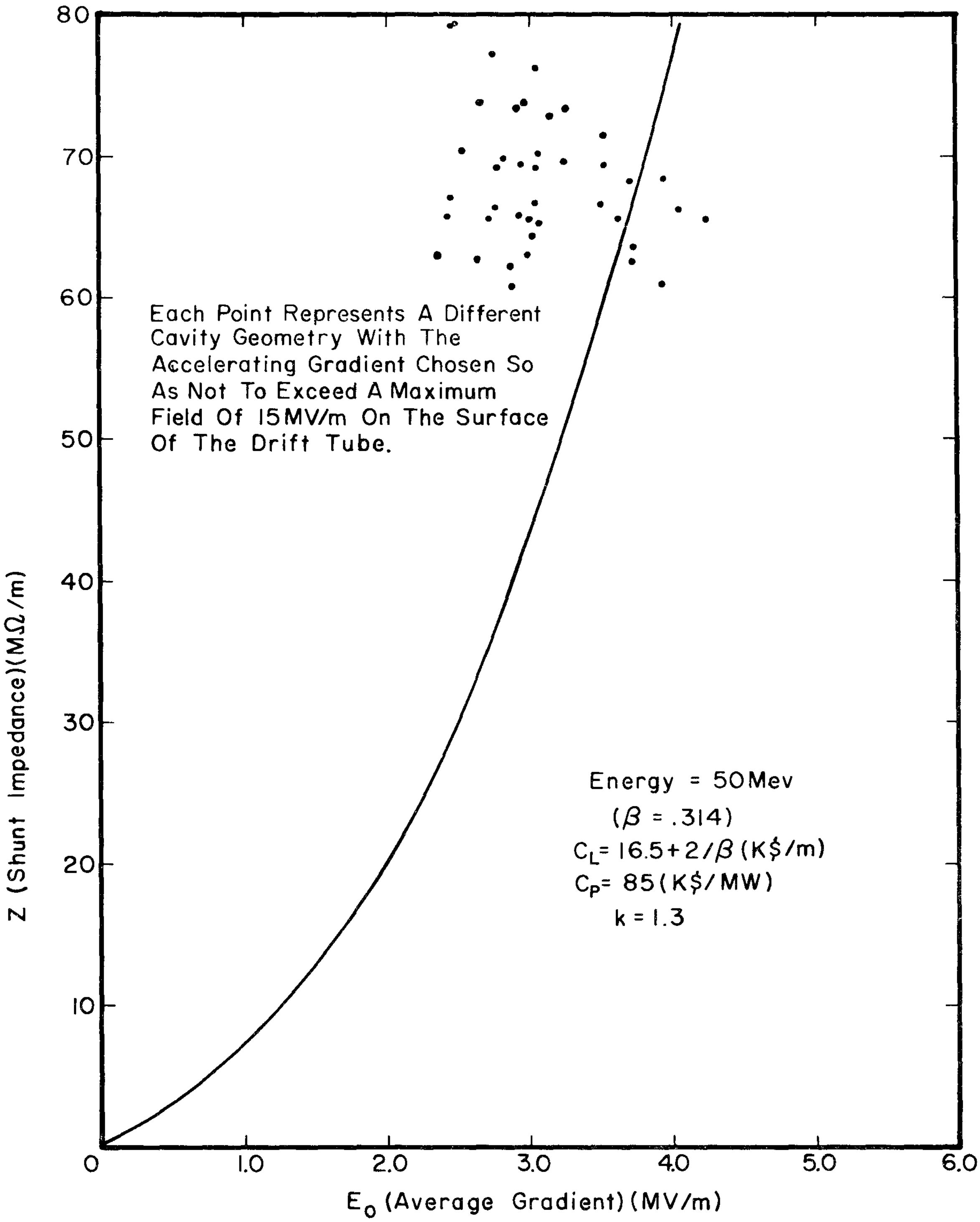

OPTIMUM ACCELERATING GRADIENT AS A FUNCTION OF SHUNT IMPEDANCE AT 50 MEV

Fig. 1