DESIGN OF DRIFT TUBE LINACS

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The Yale Design Study of Linear Accelerators has as its goal the proof of feasibility and the preliminary design of a proton linac of the "meson factory" type. This calls for an energy between 500 Mev and 1 Bev with an average beam current of 1 ma. This is 1000 times more intense than any existing proton accelerator in this energy range. At the present, a 5% beam duty cycle, leading to a peak current of 20 ma is being considered.

Part of the effort in the past months has been devoted to the low energy portion of the machine. A preliminary design for a drift tube linac up to 225 Mev has been developed. It should be emphasized that this design is preliminary and will be modified in future detailed studies. It is, however, adequate for the purpose at hand.

There has been much experience with drift tube linacs up to 70 Mev. As is well known, this type of machine suffers from increasingly severe power losses as the particle velocity increases. It is thought here that the transition to a different type of structure becomes economically desirable in the range of 200 to 250 Mev. For other structures, the Harwell π-mode structure and the quadrupole drift tube structure have been considered but neither seem promising. Consequently a direct transition to an iris-loaded waveguide seems to be indicated.

A frequency of 200 Mc/s has been chosen for the drift tube linac, for which there is ample precedent. It should be noted, however, that in a machine in which one plans to make a transition to another type of structure operating at a higher frequency, there is some cause for considering the use of a higher frequency from the start. The possibility of starting at 400 Mc/s was considered, but no solution could be found to the problems of fitting bore tubes and magnets into drift tubes at this frequency, at least until fairly large values of β are reached. It is suggested, for instance, that injection might be accomplished into a 400 Mc/s linac from a tandem Van de Graaff. However, a tandem is clearly not suitable as an injector for this accelerator. In fact, any type of Van de Graaff machine is not suitable for two reasons. Being pressurized, an excessive amount of time would be required for source maintenance. At the present time, 50 to 100 hours seem to be about the filament life for a duoplasmatron source. Furthermore, it would be very difficult to maintain the output voltage constant during a 2 millisec, high current pulse, when a stability of the order of 0.1% is required. These considerations dictate the choice of a 750 kev Cockcroft-Walton injecting into a 200 Mc/s linac.

The source should be capable of delivering a pulsed current of between 80 and 100 milliamperes. The only source which seems capable of this current for long pulses is the duoplasmatron which has been extensively developed in a number of laboratories. Since these sources are now operating at approximately the desired level, it is planned to use a duoplasmatron. No detailed design consideration will be given to the source at this time. However, the beam from this source tends to diverge rapidly because of the high current density at the exit aperture, and considerable care is needed to focus the proton beam at the entrance to the first cavity. Even under the best circumstances, it is likely that the emittance of the beam will be too large and some particles will be lost from this cause.

The space and power requirements for a duoplasmatron and its associated equipment is quite modest. However, it is intended to use polarized sources with this accelerator and so the source terminal should be made large enough to house this type of equipment. A conventional buncher is planned. The entire injection system is quite conventional and within the present state of the art.

The linac has been divided into seven cavities. The first cavity is designed as a conventional Alvarez type of accelerator using cylindrical drift tubes with quadrupole focusing. No attempt has been made to use shaped drift tubes for three reasons: 1) shaping the drift tube leads to very little improvement in shunt impedance for these low values of β; 2) the method of calculating drift tube shapes, as introduced by R.L. Gluckstern*, has not been extended yet to calculate shapes below a value of $\beta = 0.2$; and 3) the maximum space is needed inside the drift tube for the quadrupole magnet. A value of synchronous phase has been chosen, $\phi_s = -25.8^o$ ($\cos\phi_s = 0.9$) for reasonably high efficiency.

A simplified design procedure has been based on the design of the heavy ion accelerator poststripper cavity since the range of β is similar. The ratio of cavity and drift tube diameters to wavelength and the variation of g/L with β have been taken from model measurements for the Hilac. The cavity is designed for constant gap gradient, E_g = 8 Mv/m, this value being as high as seems safe. A constant drift tube diameter has been used, although g/L and the transit time factor are becoming poor at the high energy end. The length of each cell is calculated as $L_n = \beta_n \lambda$, where β_n is the particle velocity at the beginning of the cell. The energy gain for the cell is then calculated:

$$\Delta W_n = E_g \, g_n \, T_{on} \cos\phi_s \,.$$

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The transit time factor for the axial particle is given by:

$$T_{on} = \frac{\sin(\pi g/L)}{(\pi g/L)\ I_o\ (2\pi a/L)} \quad ;$$

where a is the bore tube radius. The value of β_{n+1} is then calculated from the new energy at the end of the cell. These calculations are then repeated for each cell and result in a "drift-tube table". The approximations involved here introduce errors of only a few percent.

The phase and energy acceptance of this cavity are calculated after L. Smith. The phase acceptance is approximately $3\phi_s = 77^o$. The maximum energy spread (for $\phi - \phi_s = 0$) which is acceptable is ± 52 kev.

Cavities No. 2 through 7 have been designed using shaped drift tubes to reduce the losses. For ease in calculation, "single charge" drift tubes, as evaluated by R.L. Gluckstern, have been used. It is known that this approach will not lead to the best design, i.e. minimum losses, but it is adequate in the preliminary design. Later, some improvement can be realized by employing the more efficient drift tubes calculated by the "multiple charge" methods.

A program has been written for the I.B.M. 709 computer, which is essentially a multiple interpolation routine for obtaining a continuous drift tube table from a discrete set of shaped drift tubes. The input for this program was obtained from the output of the "single charge" drift tube program, as calculated by R.L. Gluckstern. The drift tubes and cell configurations, as calculated by R.L. Gluckstern, are characterized by the following parameters:

- β - particle v/c
- b/λ - dimensionless cavity diameter
- R_{DT}/λ - dimensionless drift tube radius
- g/L - gap to cell length ratio
- T_ℓ - longitudinal transit time factor
- r - the ratio E_{max}/E_{av}
- R_s^{-1} - effective shunt resistance (μmho m)

In studying a set of these configurations in the range $(.2 \leq \beta \leq .6)$ the value $(b/\lambda)_{opt}$ as a function of β is obtained, where $(b/\lambda)_{opt}$ is the b/λ such that R_s^{-1} is a minimum at a given β. To design a tank of constant diameter an input β_i to the tank is selected and a reasonable guess of ΔW, the energy gain through the tank is made, which yields an approximate output β (β_o). It is then possible to select a $(b/\lambda)_{opt}$ for the tank from $(b/\lambda)_{opt} = f(\beta)$.

Having chosen the parameters $(b/\lambda)_{opt}$, β_i and β_o for the tank in question it is now possible to set up the input for the shaped drift tube table program. The following quantities are "input":

λ - free space wavelength (m)

E_{max} - maximum field gradient (Mv/m)

L_T - approximate tank length (m)

ΔW - approximate energy gain through tank (Mev)

$\cos\phi_s$ - cosine of synchronous phase

β_i - injection β for the tank

a - drift tube bore radius (cm)

$(b/\lambda)_{opt}$

$\beta_1, \beta_2, \beta_3$, where $\beta_1 \leq \beta_i$, $\beta_1 < \beta_2 < \beta_3$, $\beta_3 \geq \beta_o$

$$\left.\begin{array}{l} R_{DT}/\lambda_{1k},\quad R_{DT}/\lambda_{2k},\quad R_{DT}/\lambda_{3k} \\ g/L_{1k},\quad g/L_{2k},\quad g/L_{3k} \\ T_{\ell_{1k}},\quad T_{\ell_{2k}},\quad T_{\ell_{3k}} \\ r_{1k},\quad r_{2k},\quad r_{3k} \\ {R_s^{-1}}_{1k},\quad {R_s^{-1}}_{2k},\quad {R_s^{-1}}_{3k} \end{array}\right\} \qquad k = 1, 2, 3$$

The last group of input represents a set of nine of the drift tubes and cell configurations calculated by R.L. Gluckstern. Thus, for example, $T_{\ell_{12}}$ represents the longitudinal transit time factor of a drift tube and cell which is characterized by $(b/\lambda)_{opt}$, β_1, R_{DT}/λ_{12}. With the assumption that the functions to be considered are second degree in form, in the intervals of interest, sufficient data are now available to perform second degree three-point interpolation. This is done in the following manner. Given the points (x_o, y_o), (x_1, y_1), (x_2, y_2) and seeking $y_i = f(x_i)$ where $x_o \le x_i \le x_2$ and assuming that the function $y = f(x)$ can be fitted by a second degree curve in the interval $[x_o, x_2]$, the y_i can be approximated in the following way.

Let

$$D = \frac{(y_2 - y_o)(x_1 - x_o) - (y_1 - y_o)(x_2 - x_o)}{(x_1 - x_o)(x_2 - x_o)(x_2 - x_1)}$$

then

$$y_i = f(x_i) = y_o + \frac{y_1 - y_o}{x_1 - x_o}(x_i - x_o) + D(x_i - x_o)(x_i - x_1) .$$

Furthermore, if it is known that the function $y = f(x)$ has a minimum in the interval $[x_o, x_2]$ then x_{min} can be found by

$$x_{min} = \frac{(x_1^2 - x_o^2) D - (y_1 - y_o)}{2D(x_1 - x_o)}$$

and

$$y_{min} = f(x_{min}) .$$

The input data are chosen such that, considering R_s^{-1} as a function of R_{DT}/λ, for each β_j the quantity R_s^{-1} is at a minimum in the interval $[R_{DT}/\lambda_{j1}, R_{DT}/\lambda_{j3}]$ $(j = 1,2,3)$. Thus, by using the above interpolating procedure it is possible to find $(R_{DT}/\lambda_j)_{opt} = f(\beta_j)$ where $(R_{DT}/\lambda_j)_{opt}$ is the dimensionless drift tube radius for which R_s^{-1} is a minimum at β_j.

Now consider the quantities g/L, T_ℓ, r, as functions of R_{DT}/λ and, by interpolation, evaluate $(g/L_j)_{opt}$, $(T_{\ell j})_{opt}$ and $(r_j)_{opt}$ where $(g/L_j)_{opt}$ is the gap to cell length ratio, $(T_{\ell j})_{opt}$ is the longitudinal transit time factor and $(r_j)_{opt}$ is the ratio E_{max}/E_{av} such that R_s^{-1} is a minimum at β_j (j = 1,2,3).

The procedure used here has given us three-point representations of the functions

$$R_s^{-1} = f(\beta)$$

$$R_{DT}/\lambda = f(\beta)$$

$$g/L = f(\beta)$$

$$T_\ell = f(\beta)$$

$$r = f(\beta)$$

all of which are optimum (in the sense of minimum R_s^{-1}) in the interval $\left[\beta_1, \beta_3\right]$ which encompasses the expected interval across the tank $\left[\beta_i, \beta_o\right]$.

It is then possible by interpolation to proceed through the tank in a cell-by-cell iteration and calculate any of the above quantities at a particular β.

The iterative procedure takes the following form. It is assumed, as a first order approximation, that the initial β_i of any cell is the effective β of the cell.

$$\text{Tank diameter (m)} = 2\lambda\ (b/\lambda)_{opt}$$

For a cell:

Initial energy W_i (Mev):

$$W_i = 938.211 \left[\frac{1}{(1-\beta_i^{\,2})^{1/2}} - 1\right]$$

Cell length L (m):

$$L = \beta_i \lambda$$

Drift tube radius R (m):

$$R = (R_{DT}/\lambda)\,\lambda \quad \text{where} \quad R_{DT}/\lambda = f(\beta_i)$$

Gap G (m):

$$G = (g/L)L \quad \text{where} \quad g/L = f(\beta_i)$$

Energy gain through cell ΔW (Mev):

$$\Delta W = E_{max}\left(\frac{1}{r}\right) L\, T_\ell\, T_r \cos\phi_s$$

where $T_\ell = f(\beta_i)$

$r = f(\beta_i)$

and T_r, the radial transit time factor, is given by:

$$T_r = 1/I_o\left(\frac{2\pi a}{L}\right)$$

Output energy W_o (Mev):

$$W_o = W_i + \Delta W$$

$$\text{and} \quad \beta_o = \frac{\left[\left(\frac{W_o+938.211}{938.211}\right)^2 - 1\right]^{1/2}}{\left(\frac{W_o+938.211}{938.211}\right)}$$

Power requirements for cell P (Mw):

$$P = \frac{R_s^{-1}}{L}\left[E_{max}\ T_\ell\ L\left(\frac{1}{r}\right)\right]^2$$

where $R_s^{-1} = f(\beta_i)$

The output β_o becomes the input β_i for the next cell and the calculation is repeated until $\Sigma L > L_T$, the desired overall tank length. The code can be run for a series of tanks each with its set of design parameters and input data for interpolation.

The results of these calculations are summarized in Table 1. Some comments regarding this table are in order.

Table 1 - Summary of Drift Tube Tanks

Tank No.	1	2	3	4	5	6	7
β_{in}	0.0400	0.2517	0.3584	0.4385	0.4946	0.5337	0.5661
W_{in} (Mev)	0.75	31.22	66.77	105.73	141.31	171.25	199.89
ΔW (Mev)	30.47	35.55	38.96	35.58	29.94	28.64	25.96
W_{out} (Mev)	31.22	66.77	105.73	141.31	171.25	199.89	225.85
β_{out}	0.2517	0.3584	0.4385	0.4946	0.5337	0.5661	0.5919
Tank Dia.(m)	0.948	0.900	0.900	0.870	0.855	0.846	0.846
Tank Length (m)	15.27	25.02	25.11	23.79	20.81	22.26	25.18
Accum.Length (m)	15.27	41.29	67.40	82.19	104.00	127.26	152.44
D.T. Dia. (cm)	17.6	10.4-13.8	13.6-16.4	16.6-18.8	18.9-20.5	20.8-22.2	22.2-23.4
D.T. Length (cm)	4.7-21.8	31.3-37.2	37.3-40.4	41.9-43.8	44.6-45.9	46.4-47.3	47.4-48.1
D.T. Bore Dia.(cm)	1.5-2.0	2.5	3.0	3.5	4.0	4.5	5.0
Gap Length (cm)	1.5-16.0	6.5-16.3	16.4-25.1	23.8-30.1	29.5-34.0	33.7-37.4	37.5-40.6
P (Theor.) (Mw)	1.79	1.19	2.05	2.44	2.45	2.48	2.08
P (Total) (Mw)	3.11	2.37	3.65	4.12	4.04	4.04	3.43
Accum. Power	3.11	5.48	9.13	13.25	17.29	21.33	24.76
E_{max} (Mv/m)	8	12	13	13	13	12	10
No. of D.T.s	72	55	42	34	27	27	29
Accum. D.T.s	72	127	169	203	230	257	286
Average R_s (meg/m)	70	54.7	37.0	27.35	22.8	18.6	16.1

The entry under P (theoretical) is the power loss in megawatts calculated by the code, and does not represent the total power required, which is listed under P (total). The calculated power does not include losses from the drift tube stems or the end wall, nor does it include an allowance for the fact that the actual surface of the resonator will have higher losses than predicted for pure copper. The P (theoretical) has been increased by a factor of 1.4 to allow for these effects. Also P (total) has included in it the power which is transferred to the beam. P (total) = 1.4 P (theor.) + IΔW. The accumulated length is the total length of tanks plus an allowance of one meter between each tank. Where ranges are shown, they are for the first and last cell, respectively. The shunt impedance listed is the average value in each tank. For tank No. 1 it is the normal shunt impedance, while in the other tanks it is as defined by R.L. Gluckstern and includes the effects of the longitudinal transit time factor.

It should be noted that three boundary conditions must be met in designing each tank; the tank must not exceed a specified maximum length, the gradient must not exceed a maximum value, and the power requirement should be approximately equal to and certainly not greater than the power output of available amplifiers. A brief discussion of these boundary conditions follows.

A maximum length is set for each tank because of the difficulty of "flattening" a resonator which is many wavelengths long. Experience at the Brookhaven National Laboratory has shown that "flattening" the AGS injector tank was a difficult but not impossible task. That tank is 22.4 wavelengths long. It is the opinion that the tanks considered here should be kept shorter than the BNL tank in order to simplify "flattening". A tank 13 wavelengths long (20 meters at 200 Mc/s) should be straightforward, and one 15 wavelengths (25 meters) still tractable. In view of the other boundary conditions, 25 meters was chosen as the maximum length. However, the results indicate that a greater maximum length may be desirable in spite of the additional difficulty in "flattening".

The maximum gradient which may be used is set by sparking in the drift tube gaps. Various data indicate that, at 200 Mc/s, gradients of 15 Mv/m should be workable. However, the gap size has an effect, and experience at BNL has shown that in the short gaps near the injection end of the accelerator, 8 Mv/m is about the maximum gradient that can be tolerated. Consequently, the maximum gradient has been limited to 8 Mv/m in the first tank, 12 Mv/m in the second tank (where some gaps are still quite short), and 15 Mv/m in the others.

The third condition involves matching the power requirement of the tank to the power capability of available amplifiers. It is obvious that the amplifier must be able to supply at least as much power as is required. On the other hand, because of the high cost of rf equipment, it is economically undesirable to use an amplifier which has a power capability which is much larger than required. Consequently, it is necessary to match the tank requirement closely to the capability of the amplifier which is chosen. The decision has been made that the most economical power amplifier for this service is one rated at 4.0 Mw peak power output.

Ideally, then, one wishes to design a tank with a gradient which leads to the optimum combination of power and length but in which the length does not exceed 25 meters, the power required is 4.0 Mw and the peak gradient does not exceed 8, 12 or 15 Mv/m depending on the drift tube gap length. The tanks, as calculated here, meet the conditions of length and gradient but in several cases require substantially less than 4.0 Mw of power. In no case is the gradient at the optimum value. For an economically optimized accelerator it can be shown that the average gradient $E_o \propto \sqrt{R_s}$. The decreasing gradients in the last few cavities are due to this effect.

Mention has been made of the possibility of using a short (perhaps 10 Mev or less) first tank. This would give much flexibility in handling the problems encountered with the early drift tubes without being hampered by economic considerations. This seems like a desirable plan and will very likely be incorporated in a later design.

Discussion

J. P. Blewett (BNL): Regarding the choice of a 750 kv non-pressurized Cockcroft-Walton, there are people who have built pressurized Cockcroft-Waltons to obtain higher voltages.

G. W. Wheeler (Yale): Yes, but one of the complications we did like to avoid is a pressurized machine. The best figures we have heard indicate lifetimes of the order of 100 hours for a duoplasmatron filament and I think depressurizing a machine, to change a filament, then pumping back up every 100 hours, gets to be something of a problem as compared to just changing a filament in about 45 minutes.

L. Smith (LRL): Have you considered the possibility of using polarized protons?

G. W. Wheeler (Yale): Yes. We would certainly like to have this machine available for polarized protons, and I think that this means you want a big space in the terminal. This certainly points to a non-pressurized type of device.

L. Smith (LRL): How about a tandem Van de Graaff?

G. W. Wheeler (Yale): Possibly a tandem, but I wonder if you want to take that much more of a loss in beam intensity.

E. D. Courant (BNL): Stripping in a tandem machine could possibly depolarize the beam.

V. W. Hughes (Yale): This has been considered quite a bit, and I do not think anyone knows yet how to get a polarized beam first in the negative stage and then through the stripping channel.

G. W. Wheeler (Yale): But, even if you accomplish this, then you are still faced, for the high intensity application, with a tandem Van de Graaff which could not even hope to handle the very high currents. You have two separate injectors then, and I think that at this point, we do not even want to consider this kind of involved injector.

R. P. Featherstone (Minnesota): If you fix the tank diameter, and then choose the drift tube diameter with losses in mind, then the only thing you have left to tune with is gap length. Is that it?

G. W. Wheeler (Yale): But you have already included this effect. The gap length has an effect on the transit time factor but this effect is included in the definition of the shunt impedance. When you make the determination of the optimum drift tube diameter, you have already included the effect of gap length.

R. P. Featherstone (Minnesota): You started with no preconception of gap length but this is also a variable quantity which should be optimized?

G. W. Wheeler (Yale): It is related to the drift tube diameter, in that at a given value of β, if you change the drift tube diameter, you end up necessarily changing the gap length also, in the opposite sense.

L. Smith (LRL): The limitation really meant then is the peak electric field.

G. W. Wheeler (Yale): Yes, this is a restriction and not a trivial one either, particularly at the low energy end. A peak field of 15 Mv/m is felt to be as high as is safe.

J. P. Blewett (BNL): Of course at Stanford they run at higher fields.

G. W. Wheeler (Yale): But that is not at 200 Mc/s.

R. B. R-Shersby-Harvie (CERN): May I suggest that the optimum field depends also on the cost per unit length.

G. W. Wheeler (Yale): Yes, there is another factor in the expression for the economically optimum field, which directly involves the cost of components. However, for a given section of a machine such as this, this factor is constant, even if you drop the field considerably to reach the optimum point.

J. P. Blewett (BNL): There is just one comment that I want to make related to our experience; practically all of our troubles inside the tank have been in the first 5-10 Mev. In a new accelerator it might be preferable to build the first 10 Mev in a separate tank.

G. W. Wheeler (Yale): One might consider a rather short first section, so that one could then go to a higher gradient much before 30 Mev, perhaps as you say at 10 Mev.

K. Johnsen (CERN): I think there is much to be said for obtaining the first few Mev in a separate tank, disregarding economy and only taking into account beam dynamics. Also it is normally the input end of the linac that limits the current, or the acceptance rather. For these high current ion sources, it turns out I think that the intensity per unit area in phase space has not really increased, but larger emittances with larger currents are obtained.