A POSSIBLE APPROACH TO THE INITIAL ADJUSTMENT OF A LONG LINAC

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In existing proton linacs, the maximum number of independent cavities is three. No serious problems have been encountered in adjusting the field level in each cavity and the relative phases of the cavities to the proper values. However, the initial adjustment of the multicavity linacs which are now being discussed[1] is a much more difficult problem. The reasons for this are clear. The effect of an improper adjustment at one point in the linac generally will not be observed until the beam has passed through several more cavities so that there is no direct way of determining the location of the improper adjustment. Furthermore, the adjustment of a particular cavity interacts with those for the following cavities. Initially, the setting of the quadrupole magnets is not very critical and it will be supposed that they can be set to the calculated values with sufficient accuracy to assure retention of the beam. Thus there are two major adjustments per cavity: the field level (E_o) in the cavity and its phase relative to the preceding cavity. Consequently, for the new linac injector proposed by the Brookhaven National Laboratory there are 122 adjustments.

There are two important stages in the adjustment. The first is an adjustment which is sufficiently good to assure the acceleration of the entire captured beam without the loss of particles at high energies. Numerical calculations indicate that if the field level is held to ± 1% and the intercavity phase to $\pm\, 2^o$, this situation will exist. The second stage of the adjustment involves reducing the beam energy spread and emittance to the smallest values which can be achieved. The success of these linacs particularly as injectors will be determined by the extent to which the adjustment errors can be reduced toward zero. It is generally agreed that the energy spread and emittance of a perfect linac would be entirely adequate for injection into a large synchrotron.

If all of the characteristics of the beam could be accurately measured at the end of each cavity, there would be no difficulty in adjustment. This unfortunately is impossible. The following quantities can be measured as indicated.

a) W and ΔW, the beam energy spread.

These quantities can be measured by magnetic analysis. Consequently the measurements can only be made at the injection point, at the transition section and at the end of the accelerator. Beams of less than full energy may be drifted through the accelerator to the magnets without destroying the desired information. Accuracies of about 0.1% can be achieved. An alternative method involves time-of-flight techniques but requires considerable equipment and space.

b) I, the beam current.

Absolute measurement of the peak beam current is difficult but is not necessary for accelerator tune up. Relative measurements may be made with ease and considerable accuracy using beam current transformers. The transformer output is independent of energy and relative readings can be accurate to better than 1%. Thus if several transformers are calibrated relative to each other at one point, they may then be distributed along the accelerator and the differential outputs from them will be a sensitive measure of beam loss along the accelerator. However, the sensitivity of the transformers is only about 10 μA so that a peak beam current of at least 100 μA is needed for good measurements. Another sensitive method of detecting beam loss is to locate neutron or gamma detectors close to the structure to detect radiation due to lost beam. This system gives somewhat more detailed information as to the location of the beam loss.

c) The beam emittance.

The beam emittances can be fairly readily measured at low energies with considerable accuracy. At higher energies, the measurement can be done less readily. The measuring equipment is bulky and can be provided only at the injection point, at the transition and at the end of the accelerator. Some simpler systems which will give a rough measurement of x and y may be placed at more frequent intervals between cavities.

d) E_o, the average accelerating field in each cavity and φ_s, the synchronous phase.

An absolute measurement of E_o can be made to between 5 and 10% with carefully calibrated pickup loops in the cavities. A relative measurement of E_o between two cavities can probably be made to a few percent, and E_o may be held stable to 0.1%. There is no direct measurement of φ_s. If the energy gain in a cavity can be measured, then $E_oT \cos \varphi_s$ is known to the same accuracy. The transit time factor, T is fairly well known from cavity calculations. If E_o is decreased until $\varphi_s = 0$, it is possible in principle to measure the threshold value of E_o for which particles just gain the synchronous energy. This involves measuring a very small current and consequently has limited accuracy.

e) $\Delta\varphi$, the phase spread of the bunch.

The phase spread of the bunch can best be determined from a knowledge of ΔW. The center of the phase bunch may be measured with poor accuracy by observing the phase of a small resonant cavity between the accelerating cavities. This cavity will be excited by the beam at a phase corresponding to the "center of gravity" of the bunch.

f) $\Delta\varphi'$, the phase difference between adjacent cavities.

The phase difference between two cavities can be measured absolutely to a few degrees. The design value can be calculated accurately. The setting can be held to better than 1°.

The following general procedures will be followed in order to tune up the accelerator with a minimum of activation of the structure. Initially, short beam pulses and reduced repetition rate will be used. The peak beam current will be limited to about 100 μA to remove the beam loading problems from the first tune-up attempt. The drift tube section should be completely tuned up before a serious attempt is made to tune the waveguide section. All measurements of the output beam from the drift tube accelerator will be done in the transition region between the two sections.

In what follows, it will be assumed that the beam from the drift tube section of the linac has been adjusted for best quality and that the transverse focusing of the beam in the waveguide section is well enough adjusted so that all particles which are longitudinally stable will be radially stable. The following procedure is suggested as a possible method of adjusting the waveguide section of the linac. Very extensive numerical calculations are needed to demonstrate that the procedure will actually lead to the desired result. Some preliminary calculations have been made using a program[2] which treats only the longitudinal motion of the axial particle.

If the field level (E_0) in each cavity and the phase difference between cavities ($\Delta\varphi'$) are set by absolute measurements to the design values, it is to be expected that particles will be lost at various points along the accelerator because of the errors. However, if the size of the bucket in each cavity is substantially increased, the entire beam can be retained in spite of sizeable errors in $\Delta\varphi'$. Since the initial tune up will be carried out at low beam current, the amplifier output, which will ultimately be transferred to the beam, is available to increase E_0 above the design value. Calculations have shown that if E_0 is increased by 15%, the entire beam can be retained for errors in $\Delta\varphi'$ of $\pm 5^{\circ}$ or more.

Since the design value of E_0 should be well below the sparking limit, a 15% increase in E_0 is possible. This will increase the bucket width from about 77° to about 115°. Throughout this procedure, the beam current is carefully monitored at several points along the accelerator.

The next step is to gradually decrease E_0 in the first cavity until a noticeable decrease in beam current occurs. It will be necessary at the same time to decrease E_0 slightly in the next few cavities in order to prevent the recapture of the particles which have become unstable in the first cavity. When the bucket in the first cavity has been shrunk so that some particles are outside of the stable region in the first cavity, the setting of $\Delta\varphi'$ for the first cavity is varied to minimize the loss. Here, $\Delta\varphi'$ is the phase difference between the last 200 Mc/sec cavity and the first waveguide cavity. This centers the injected bunch optimally in the first cavity. Now, E_0 in the first cavity can be increased by a calculated amount to the design value. This will only be approximate but the exact value is not important. It should be noted that changing E_0 causes the bucket to expand or shrink around $\varphi = 0$ and not around φ_s. Consequently, the value of $\Delta\varphi'$ which was just determined is no longer correct. A reasonably good calculated correction can be set in $\Delta\varphi'$ because now we are making changes in the relative (rather than absolute) values of E_0 and $\Delta\varphi'$ and this can be done with considerable accuracy for changes of this magnitude.

At this point, all but the first cavity are turned off and the energy gain of that cavity is measured. If the average energy gain does not correspond to the calculated value, the cavity field will have to be tipped to make it do so.

The whole procedure is then repeated for subsequent cavities in a sequential fashion. When measuring the beam current decrease due to shrinking the bucket in cavities near the high energy end, magnetic analysis of the output beam will be required to distinguish between particles which have become unstable and those which have not since all will emerge from the end of the accelerator.

Repeating this entire performance a second time should further improve the adjustment. Once values of E_0 and $\Delta\varphi'$ have been established for each cavity, it is the job of the level and phase servos to hold them there.

Preliminary numerical calculations indicate that the phase errors can be reduced by this procedure on the first attempt. However, the measurement of beam loss is not extremely sensitive and it will be necessary to examine the beam quality in order to achieve better adjustment. Nevertheless the procedure seems promising at first look and further computations will be carried out.

Once the whole accelerator has been tuned up in the unloaded condition, the beam current can be increased until the effects of beam loading are observed. The automatic level and phase control systems must be adjusted to maintain the correct settings. At each stage the necessary adjustments can be made until the full beam current is (hopefully) reached.

LEISS: In making this analysis, you have assumed that subsequent buckets are in the correct place. Now, if you have a systematic deviation of the location of the subsequent buckets, have you assured yourself that in fact you are not building in systematic errors which you are trying to satisfy rather than putting the beam where you would like it? It seems possible that there is a trap here. In other words, are you presupposing that the problem is already solved?

WHEELER: No, we have not presupposed a solution. It is true that we have used only random errors distributed about the correct value and have not looked at the effect of gross systematic errors. However, by increasing E_o by an amount which is greater than any reasonable systematic error we can assure ourselves that E_o is well above the design value. Our assumption of $\pm 5^o$ phase error would account for a systematic phase error up to that value. A systematic phase error larger than this could be troublesome but I think that the system is flexible enough to handle it. Let me emphasize that there is a lot more work to do before we fully understand how to apply this method of tune-up.

BLEWETT: I should think that if you have a gross systematic error, no beam will come out and you will say, "Ah ha, I have a systematic error", and will look for it.

WHEELER: Yes. I think that there are a number of ways that you can detect gross systematic errors before you turn on the beam which implies that such errors can be eliminated.

FEATHERSTONE: There are at least two possible methods of controlling the relative phase of the cavities in a long string of cavities. One is to refer all the cavities to a reference line and the other is to refer each cavity to the preceding one. Is there a preferred way of doing this when you consider the actual tune-up process?

WHEELER: Yes, I think there is although I am not sure which it is. My own opinion is that it is better to measure the phase directly between two adjacent cavities. In either case you can have a systematic error in the phase detector.

TAYLOR: For about 18 months, we have been trying to get a rather similar measurement to work but so far we have not gotten consistent results. We have tried the following measurements. You have the bunch coming from the first tank and then you collapse the bucket in the second tank until you trap only a small current. You define this as a threshold and then you raise the level a little and shift the phase of the second tank to get back to the threshold current. The lowest tank level achieved gives you approximately the $\varphi_S = 0$ level and then the other levels can be converted to the corresponding φ_S. Making certain assumptions, the result should be two straight lines ($\varphi_S = \varphi$ and $\varphi_S = \varphi/2$) and the intercepts give you the phase width of the bunch. We have tried this several times. The very first time, we got two straight lines which intercepted the axis and gave us a phase width which agreed quite well with simple theory. We repeated this later and got two more lines with different slopes which gave us different intercepts. We still think that there is some way to go before you can use this technique as a measurement for setting phases but I agree with you that it could be useful.

CARNE: I think that the success of this technique depends on the beam performing many phase oscillations in one tank.

WHEELER: This could be correct. We find from our numerical calculations that we must shrink the buckets in a group of about four tanks at a time in order to get a clear indication of particle loss. This corresponds to about one phase oscillation wavelength near 200 MeV.

DICKSON: One has to be careful about the detector used here. A current transformer will accept all energies. Some sort of threshold detector might be better.

WHEELER: When a particle becomes unstable in phase at an energy of about 300 MeV or more, it will emerge from the end of the accelerator, even though its energy is incorrect. Magnetic analysis can be used to determine when particles have not been fully accelerated, or one can use a threshold detector as you suggest.

TAYLOR: I want to point out that this setup problem may be with us in 5, 6 or 7 years but that in the meantime the methods of measuring beam properties may have advanced to the point where one can get all of the information required for a rational setting up. It does make one wonder about the distance between the tanks and if there are some tricks that can be used such as changing the stability limit at the end of the previous tank, as Lapostolle has suggested, to allow a little more space between tanks. I think that this would pay off.

PERRY: It seems to me that one might start at the high energy end to measure the E field level and determine from the energy whether or not you are above the accelerating gradient and then go progressively up the line toward the front end to determine what accelerating gradient you must have.

WHEELER: I don't think you can learn much about the proper phase setting by this approach.

PERRY: This is true, but it seems to me that knowing this gradient to begin with before you start worrying about phase you have an easier job in the phasing problem. You know how high you have to go to get 15% above accelerating gradients, for example.

FEATHERSTONE: I wonder if Blewett's technique of using the upper tail of the fish as a rather precise probe could be adapted to this technique?

WHEELER: I think that it can be done and could be of additional help.

REFERENCES

1. See for example:
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2. G. W. Wheeler and T. W. Ludlam, Minutes of the Conference on Proton Linear Accelerators, Yale University, October 1963, p. 29.