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RF POWER SOURCES

D. C. Hagerman
Los Alamos Scientific Laboratory

I will review the thoughts of the Los Alamos people on the type of rf power sources required for linear accelerators. First, let me remind you that all of our thinking is strictly in the framework of meson factory applications; we are only thinking of accelerators which would give us an energy of 800 MeV, duty factors of about 5%, and pulse lengths on the order of a millisecond. The 200 Mc/sec rf problem seems to be solved by the 7835 in use at the ZGS. We think it is clear that there has to be a transition in frequency, because of the variation of shunt impedance as a function of beta. We think that the transition should occur at a particle energy of between 150 and 200 MeV. From beam dynamics, you can show that the harmonic ratio of this frequency transition should be no greater than 4; however, 4 is probably satisfactory, so we conclude that the frequency of the higher energy portion of the machine is 800 Mc/sec. Also, beam dynamics shows that phase control is quite important; we typically think in terms of $\pm 1^{\circ}$. This number will change somewhat as the beam dynamics study goes along. The amplitude control of the rf power also has a strict requirement on it, namely of the order of ±1%. The last time we talked to the Yale Group about this, they spoke of even a tighter power requirement, like 1/10%. Further, we believe that the shunt impedance studies show, when combined with the moding problem studies, that the optimum power package is of the order of 1 MW. We don't claim a precision on this number of greater than 25%.

With these few statements in mind let us compare gridded tubes and klystrons. The first thing to consider is the control sensitivity. If you look at the characteristics of the triode, you find that if the anode supply voltage changes by 1%, you'll see something like a 1^o change in phase shift across the tube. Whereas, in the klystron, if you change the high voltage by 1% you see a 6^o change in phase shift. Clearly the triodes are superior here. Further, you find that in the triode if you change the drive from 15% to 100% of saturation, the phase shift again only changes 1%. The klystron phase shift is more sensitive to changes in drive level than this. This is important because certainly it is desirable to have the phase control problem as far decoupled as possible from the amplitude control problem. So again, the triode is superior. Also, triodes operate at considerably lower voltages than do klystrons. Triodes or tetrodes have typical anode voltages of 25 kV; most of the klystrons at the desired power levels require voltages of 80 to 120 kV.

The next factor which enters is the cost. The vendors tell us that the direct package cost for either a klystron or triode is around $15,000. Gridded tube lifetimes are ~ 25,000 hr;[1] klystron lifetimes may be as high as 5,000 to 10,000 hr.[2] This means that the cost per hour of the klystron is ~ $2 per hr; the cost of the triode is like $0.50 per hr. The efficiency of the tubes is about the same, so the over-all power consumption of the machine is about the same for either type. The indirect costs again favor the triode. Triodes do not have to be replaced nearly as often as do the klystrons. This means that the down-time is considerably less. The klystrons are quite sensitive to high voltage standing wave ratios, which certainly will occur during the filling time of the resonant cavities. Isolators are then required to protect the klystrons. Isolators are not required for triodes. These isolators will be expensive items and something like 50 of them would be used. The klystrons also have the minor disadvantages of requiring magnets and producing x rays. As far as we can tell, the availability of either tube is about the same. At this time we are fairly well convinced that the triodes are far superior to the klystrons.

I should also mention that there is another tube called the amplitron, which is a derivative of the magnitron family. As far as we can tell, the amplitron has all of the disadvantages of the klystrons plus a few more. We don't think it should be considered at all.

FEATHERSTONE: You said that the efficiency of the triode and of the klystron are approximately the same. I assume that you are taking into account the losses of the necessary series plate modulator required with the triode which would not be required with the klystron using a modulating anode.

HAGERMAN: That's right.

WHEELER: I agree completely with the desirability of the triodes. However, the manufacturers are making very significant improvements in their klystrons over the type of performance we have been talking about. They admit that phase shift as a function of beam voltage is still a large factor such as was quoted. However, they talk with great confidence about regulating the 100 kV of dc to 0.1% which seems to me to be far from a trivial job. These large tubes, of course, have modulating anodes so that the output power from the klystron can be varied by varying the mod-anode voltage, with fairly low power devices and without changing the beam voltage. So hopefully, one could get some output power variation through the use of a modulating anode without running into the problem of output phase shift due to changing the beam voltage. They say admittedly that the phase shift through the tube as a function of drive power is a serious problem, but they make the following argument which is fair: that if you take a klystron with a gain of 40 db and compare it with a triode with a gain of 10 db, you need four triode stages to do the same job. In each one of those stages, you have a phase shift due to drive level and plate voltage.

HAGERMAN: Certainly, you require more drive stages with triodes, but I think it is quite reasonable to control the phase in the tube immediately preceding the final instead of controlling the phase way back in the drive chain. Also, I simply don't see any reason to put yourself in a position where you have to develop a tenth of a percent voltage regulator when you can probably get away with a 1% unit.

WHEELER: I think our present indications are that you need about 0.1% stability of the rf in the cavities.

HAGERMAN: Well, I'm talking solely of the fact that no matter what the rf levels requirement in the cavities are, we would require nearly an order of magnitude better regulation of beam voltage in the klystron than in the anode voltage of the triode to achieve the same stability.

HUBBARD: I'd like to ask what is the cause of failures in the klystrons being used here at Yale?

SHEEHAN: I think it's the windows. However, when a window goes it is hard to tell from what is left, what started it. The failure is usually in the form of small pinholes in the window.

HOOVER: I'd like to interject here with regard to window failures, that this can be a common problem with any type of generator depending on how the window is configurated. There are new window designs that one can undertake, with different types of tubes. The reason I mentioned this is we have ourselves tangled up in window designs for klystrons, and whatever is behind the window is somewhat irrelevant. The kind of peak power one is running, the frequency, the window configuration, and other things determine the problem.

LAMB: The present high powered triode, I think you'll agree, better have an isolator because it has got a spider web grid in it and without isolators tank sparks will wreck the tube.

HOOVER: It depends on what kind of spider web it is. If it's a radiation cooled spider web which is not intensely cooled, obviously it will only take but so much abuse. This sensitivity of the grid to tank sparks between drift tubes depends on tube construction. It is true that the line of super power triodes, such as the 7835 have spider web grids. This is where they get their performance. On the other hand, we have introduced a degree of cooling to them that just hasn't been available heretofore. For instance, we have tested the big tubes for 40 kW of c.w. power into the grid structure without any evidence of any difficulty. We have run repeated sparking tests deliberately between grid and plate in bell jars and the lightening seems to want to strike between the ribs and the plate. And even where it does strike the grid, the grid is running stone cold to start with. So it takes a degree of abuse which is even better than that of the classical rodded grid such as is in the shielded triode. The grid of the shielded triode is already running at 1000°C before anything happens. Consequently, I don't think that we can compare the spider grids of 20 years back, with the sort of spider grids that are used now in the super power tubes. I've also had the opportunity to look at about 11 tubes, of the 7835 category, that have failed in radar applications. I am happy to say that in these 11 tubes not a single wire was burned. I should say what has been the cause of failures. In the 7835, to date, they've had to do with circuit fires, invariably due to improper connections in the grid terminals. The contact fingers start running hot and the next thing you know they're burning holes in the grid flanges and after that happens the tube goes down to air.

HUBBARD: In the sparking tests that you mentioned on these grids, how many joules were you putting into the spark?

HOOVER: I think it was in excess of 300 J being dumped into the continuously pumped system with one unit without any apparent damage. They are also mechanically strong, the secret being that the tungsten spans are only of the order of 0.160 in. I don't want to indicate that there is never going to be a burned grid wire because this is obviously fallacious. However, I want to indicate that there is a degree of strength there that doesn't at first meet the eye.

HUBBARD: Do you think that you could conduct the heat out of one of these wires over to the bar during the spark?

HOOVER: No, not during the spark, but the point I wanted to make is the fact that it is cold to start with, whereas the classical grids are ordinarily running at about 1000^{o}C before anything happens. This is a terrific differential. They are also tungsten, of course, so they will take quite a little heat. With regard to Lamb's question, there is a difference between the shielded triode and the grounded grid triode. In the grounded grid triode, the lightening does not want to strike back at the cathode circuit because in your grounded grid the fireworks occurs between grid and plate. The curse of the shielded triode (in addition to its advantage), is that for reasons that are not quite understood, despite the shielding, there has been a lot of evidence that fire starts to play around the cathode strands. I don't know why this is. We've had occasion recently to look at a Yale tube that had been run about 15,000 hr. and its cut off characteristics had started to vary. We took it back, cut it open and found that the tube looked beautiful inside except for the fact that one cathode strand had gotten nipped somewhere, how I don't know. So it started to neck down until it gradually stretched longer and longer and finally came out into the stream. There was evidence in that tube that there had been fireworks playing around the cathode, back in this labyrinth, yet the rest of the tube was all right. I have a feeling however, that in the grounded-grid construction of circuitry that this is not going to happen because of the low impedance between grid and plate. We have similar problems in klystrons involving discharges due to multipactoring. I'm sure that you have seen multipactored drift tubes. Well, precisely the same sort of thing goes on between the gaps in klystrons. I'm about as much concerned about multipactoring chewing on the lips of klystron gaps as I am about spider grid problems.

FEATHERSTONE: I take it then that you feel that applications such as Argonne has, in which a tube of the type you were talking about is being fed into a large cavity with plenty of stored energy without an isolator are essentially reasonable applications.

HOOVER: Based on the experience to date, it is not a matter of major concern. I should say that this development at Argonne has proceeded without damage to a tube. The Cambridge electron accelerator project has likewise been carried this way. The Phermex machine has also gone without damage to tubes, and no isolators.

POLK: The FTH tube in the CERN and Brookhaven machines have run well without any sign of trouble.

FEATHERSTONE: Those two are much smaller tubes with a much more conventional grid design, as I recall.

HOOVER: This is a classical gridded tube, and that grid is running in the order of 1200° to 1300°C. It has to because it is on the ragged edges of taking off, and yet from all I can hear there haven't been any damages to these so-called spider grids. It's a very fragile grid compared to that in the 7835.

FREYMAN: The people who talk klystrons always like to refer to the low driving power required to driver a klystron without pointing out that the plate efficiency is 10 to 15% lower than a gridded tube and the corresponding power bill is going to run as high or higher for a klystron over a given period of time. Another thing which both people who build triodes and klystrons like to ignore is that not only do you have a long term phase stability problem in both types of tubes but you also have a short term phase stability problem.

FEATHERSTONE: People have been matching pairs of klystrons into a single load using hybrid junctions and now have reported that the phase and the amplitude of the signals from the two individual klystrons must be matched closely if the power is to be delivered into the desired load and the unbalanced power goes into a wasting load. Ratios of the order of 10^4 between the power delivered to the desired load and the power delivered to the wasting load were claimed.

WHEELER: I would like to add an experimental point on phase control, based largely on work that Sheehan has done on the Heavy Ion Machine. We look at the phase between the two cavities on a phase detector which is sensitive to better than one degree. These two cavities are driven by separate amplifier chains with no regulation on any part of the circuit. The short term variation, that is, the variation in phase during the body of the pulse is not detectable.

SHEEHAN: It is considerably less than half a degree.

References

(1) Operating experience on the Heavy Ion Accelerator at Yale indicates an average lifetime of more than 15,000 hr. for the type of 6949 super power triode. Other super power triodes have demonstrated lifetimes between 20,000 and 40,000 hr.

(2) J. F. Hull, Microwaves, 2, 22 (1963).