HIGH FIELD MEASUREMENTS AT 200 MHz IN CONVENTIONAL PROTON LINEAR ACCELERATOR GEOMETRIES AT 5, 50, and 130 MEV*

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Since the first linear proton accelerator was built, it has become increasingly clear that one of the most important design parameters is the average axial accelerating field, E_o. The current practice is to choose a value of E_o low enough to insure no sparking difficulties, arguing that the increased costs involved in building a longer accelerator structure will be more than offset by the gain in reliability. Such a view is certainly reasonable since many of the larger linear accelerators serve as injectors for very large and very expensive circular accelerators. In the last few years there has been interest in even higher energy linear accelerators. There has thus arisen an even greater need for relating the system reliability to the operating gradient in order to keep the accelerator size and cost to a minimum or at least a reasonable value.

A very general semi-empirical criterion, dealing with sparking, was developed by Kilpatrick[1] at Berkeley several years ago. This criterion described the minimum field values at which sparking might occur in a vacuum on electrodes made of various materials. Kilpatrick's data were taken on diffusion-pumped systems before the advent of ion-pumped systems. There are very few other rf sparking data available.

The sparking and electron emission studies which have been undertaken at MURA are restricted to 200 MHz in linear accelerator cavities of the Alvarez type with 500 μsec pulses and a 1 per cent duty cycle.

The experimental arrangement is shown in Fig. 1. It consists of a copper clad steel vacuum envelope pumped by a 400 l/sec ion pump. RF power is supplied through the 3-in. 50 Ω coaxial line to an adjustable coupling loop which is normally adjusted for minimum reflected power from the cavity.

Figure 2 is a cross-section drawing of the cavity which shows two different drift tubes installed - one 50 MeV drift tube and one 130 MeV drift tube. The power dissipated on the drift tubes, the drift tube support plates and the cavity side walls can be measured independently by measuring the cooling-water temperature rise across the element in question. Total power is measured by adding the individual powers and also by measuring the total system temperature rise. The input water temperature is very closely controlled, normally to room temperature. Temperatures are measured with carefully calibrated sensitive mercury bulb thermometers which can be read to an accuracy of about $\pm$ 0.01°C. A thermistor bridge is used for measuring the total system temperature rise with an accuracy of the order of 0.02°C. In addition to calorimetric measurements, forward and reverse power measurements in the input line are made to a probable accuracy of 10 - 20 per cent. Radiation measurements are made with ionization chambers and sodium iodide scintillators. The most important measurements are the field measurements. They are also the most difficult to make.

The MURA MESSYMESH program[2] allows the point by point E and H fields to be computed in axially symmetric linac structures of this type. The program does not take into account the presence of spring rings and other rf contacts, input and pickup loops, or surface irregularities. A number of experiments were conducted on several different cavities to verify the results of the computer program with respect to the frequency and fields. The geometrical shape of the fields was determined by perturbation techniques. Within an experimental error of about 3 per cent, the computed field values were as measured. Resonant frequencies were within 0.2 per cent of the computed values. Measured Q values were typically 80 - 85 per cent of the predicted values. Even that agreement is good when spring rings and weldments are taken into consideration.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

The computer program also gives the power dissipated in the cavity (and on the separate cavity elements) for E_o (the average axial field) = 1 MV/m. Thus, if the real Q is known and the dissipated power is measured, E_o can be calculated and the fields E and H everywhere in the cavity (except near some perturbation) can be determined from the computer program. There are several disadvantages to this method; good calorimetric measurements require very high stability-power input, water-flow rate and water and ambient temperature. They are also tedious and time consuming - a particular drawback when high level operation causes high x-ray levels near the cavity where the thermometers have to be located and read. In principle, the magnetic field at the wall of the cavity could be measured directly by measuring the voltage induced in a pickup loop of known area, but the difficulties of determining the exact area, the exact position, the perturbing effect of the loop and the accurate measurement of pulsed 200 Hz voltages preclude its use as an absolute standard. It can, however, be calibrated. Pickup loops driving diodes and very high impedance voltmeters seem to exhibit no important non-linearities in the range of interest in the test cavity.

Calorimetric calibration of the pickup loop was the technique used for field measurement in the 5 and 50 MeV geometries studied. The same technique was used in the 130 MeV geometry and subsequently checked by the following method.

The absolute value of the electric fields can be accurately determined by measuring the voltage gain of a particle accelerated by the field. This technique is slightly more involved than it might seem at first.

Figure 3 will make the problem a little more apparent. The accelerating field is constant neither in time nor in space. Another computer program, LINDY,[3] is available at MURA for orbit studies in the test cavity. It uses the fields computed with the MESSYMESH program. For simplicity, electrons are accelerated across the cavity. Computer studies give the maximum momenta of the accelerated electrons after passing through the cavity. In the experimental arrangement a small collimated electron beam is injected into the hole in the bottom drift tube support plate, accelerated across the cavity, and sent into a magnetic momentum analyzer mounted on top of the vacuum envelope. Measurement of the maximum electron momentum will then (when referred to the computed field-momentum relation) give E_o directly. Measurements made at four different power levels indicated that the calorimetric measurements gave values of E_o which were consistently 2 per cent high - remarkably good agreement. These measurements have been completed only on the 130 MeV geometry; all 5 and 50 MeV fields were computed from calorimetric measurements. Substantially similar results are expected from the 50 MeV geometry, but we expect somewhat larger errors in the 5 MeV case.

Figure 4 shows the surface field on the drift tube in terms of E_o. It should be noted that the maximum surface field is several times the value of E_o. It should be remembered that the surface field values given are for a microscopically smooth surface and that local fields near irregularities in the real surface may be many times that value.

The high surface fields cause electrons to be emitted which are accelerated across the gap and strike the opposite drift tube or the opposite end plate depending on the point of origin of the electron. When the electrons strike, they produce thick target Bremsstrahlung. Observation of the Bremsstrahlung can yield information about the nature of the surface. It has been reported in the past that above a certain "threshold" field the radiation level varies as E^n where n is a number of the order of 5. It is possible to characterize the field dependence in a more meaningful way. Although thick target Bremsstrahlung data are scarce, the published results of Buechner <u>et al</u>.[4] indicate an approximately linear intensity - electron energy relation at least up to 2.35 MeV when observed at angles near 90^o. For field emission electrons, we should then expect a relation of the following form to hold.

$$R \sim E^2 T e^{-\frac{\alpha}{E}} .$$

The kinetic energy of the electron goes approximately as E so

$$R \sim E^3 e^{-\frac{\alpha}{E}} .$$

Plots of $\ln \frac{R}{E^3}$ vs. $\frac{1}{E}$ are very nearly straight lines for all three geometries. The slopes are approximately equal for the 50 and 130 MeV cases; the slope for the 5 MeV case appears to be about twice that of the other two.

Figures 5, 6, and 7 show the fit of the field emission curves to the experimental data. A similar fit to the experimental data can be achieved with a Schottky-type thermionic emission assumption. In this case the equation is of the form

$$R \sim E\, e^{\beta\sqrt{E}}$$

and the thermionic curve is shown for the 5 and 50 MeV data. In the range of measurement either equation can fit the data adequately.[5]

In order to obtain more information on the electron emission from the surfaces, another set of 50 MeV drift tubes have been installed in the cavity. One of the drift tubes contains a plug where the bore hole would normally be. The other has a 1/8-in. diameter axial hole with a Faraday cup behind it. With this arrangement, the electron current emitted from the plug can be measured directly. Surface materials and preparation can be investigated with this arrangement with greater ease.

The data obtained on sparking have been restricted by the maximum rf power capability of the power supply. In Fig. 8, the maximum operating conditions for the three different linac unit cells are tabulated. In the 50 and 130 MeV configurations, runs have been made for extended periods of time at peak surface fields of 23 and 20 MV/m respectively. At 5 MeV, a peak surface field of 38 MV/m was achieved. Aside from the initial cleanup sparks which were observed during the initial runs with the 50 and 130 MeV drift tubes, not more than a half dozen subsequent sparks were detected, none of which was destructive to the surface. There were relatively more sparks with the 5 MeV drift tubes; a few produced craters visible to the naked eye. The sparks observed were not correlated with the fields. In all three geometries, the cleanup sparks were observed only during initial run-in. The cleanup sparking did not recur even after exposure to air for periods of 30 minutes to 2 or 3 days. After initial run-in, x-ray field data points were closely reproducible with most of the variation attributable to changes in the placement of the shielding around the cavity.

All tests have been made using OFHC copper drift tubes which were machined and polished mechanically, then cleaned and subsequently handled in a manner consistent with good vacuum practice. The sparks were defined as discharges which cause a breakdown of the rf in the cavity.

The experiences to date have led to several conclusions which do not seem to be in disagreement with the experiences of operating linacs. First, all of the "new" surfaces were subject to cleanup sparks which commenced at fairly low field levels and then actually subsided at the higher levels. After the cleanup sparks, sparking occurred very rarely at the maximum field levels attained in the 50 and 130 MeV geometries. Second, after reaching some high rf level in the cavity, the subsequent operation at a lower level was always quiescent. Third, at the higher field values the x-ray levels arising from the electrons emitted from the surfaces are appreciable. These levels can be reduced by changing the work function of the surface so as to reduce the electron current. As an example, the 50 MeV drift tubes were plated with a thin layer of rhodium and at the same rf level in the cavity, the x-ray level was reduced a factor of 5. The thickness of the rhodium layer was small compared to the rf skin depth so that the surface resistivity was not appreciably affected by the treatment.

References

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2. T. W. Edwards, "Proton Linear Accelerator Cavity Calculations", MURA-622 (unpublished, 1961).

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DISCUSSION

C. A. RADMER, MURA

FEATHERSTONE, Univ. of Minnesota: Do you estimate that any significant amount of the rf power you are putting into the cavity is going into x-rays at the higher radiation levels?

RADMER: Yes, certainly into electron power being dissipated on the surface in the form of heat. We, in fact, were able to measure this calorimetrically by measuring the power, i.e. the percentage of power dissipated on the drift tube. This would give us, at the very high powers, an increased ratio of several percent over the low power distribution.

VAN STEENBERGEN, BNL: How do the maximum field values compare with the limit set by the Kilpatrick criterion?

RADMER: The Kilpatrick criterion has set the maximum field value at 14.7 MV/m, compared with 20 and 23 at the high energy end where we had very few sparks. This is a one-cell unit, however, and the probability of getting sparks in a long tank will be much higher.

PARKER, LASL: You made a statement regarding the temperature dependence; I think you said the radiation tripled over a certain temperature range. What was that temperature range?

RADMER: More exactly from 4°C to about 80°C.

PARKER: I was wondering if you might have made any x-ray spectral-dependence measurements?

RADMER: No, we haven't.

PARKER: It might be interesting to note that we did. Of course, we did it on a cloverleaf cavity. We found that while there was a very strong dependence of bremsstrahlung on the power level (in fact it went about as a six power of the power level), there was no change in the spectrum.

ALLISON, Berkeley: I would like to comment that, in our machine sparking takes place in the first 15 drift tubes. Sparking occurs on the first pulse with beam on and on the following pulse when the beam is turned off. This is probably caused by transients in the regulation system. We started out with our drift tubes silver plated. We now have no silver left on them, and if you look in the linac cavity, you can see a pile of what is now mostly copper. It was silver for the first two years, and when we looked a year ago, the silver was gone so that now we are eroding only copper and solder. A considerable amount of erosion occurs. It is very smooth, however; there is no pitting on the drift tubes. It seems to be coming off the drift tube faces and about 4 in. up on the stems. Our front end gradient is high. It's the highest gradient part of the tank. This sets the operating limit we run on our machine for synchronous phase (18° instead of 26°).

RADMER: Does this show up on both sides of the drift tube also?

ALLISON: Oh, yes.

RADMER: One thing I did omit is that on the 5-MeV drift tube, with which we did have quite a bit of sparking, we did see pitting which, in fact, was not related to the electric field in any reasonable way. Sparking occurred both on the flats and outer radii.

PERRY, ANL: I have a remark similar to that of Allison's. The sparking evidenced in the Argonne machine is all in the low-energy end. We do see a considerable amount of sparking in the first gaps; this extends down to about 5 MeV. There is nothing in the high-energy end on any of the drift tubes.

B. SMITH, LRL: This is kind of a request for an experiment that I have wanted to try but never had a setup like this to do it. You just might be interested in it. There is a process called hydrogen scrubbing that is used on dc electrodes for reducing electron emission. It typically reduces the electron drain current, that is, the dark current that occurs just before sparking, by about a factor of 10 in a comparatively dirty system. Let me describe it in case you are not familiar with it. On the deflector in the 88-in. clyclotron at Berkeley, after the machine has been in use for a long time, they will find that the electron-drain current, at just below the sparking level, will go up to about a mA; whereas, if everything is clean, it will be about a tenth of that, or 100 μA. They let the tank down to about 100 μ of hydrogen, and then, by means of a little 440-volt transformer from 60 cycles, which they attach to the deflector electrode, they run a discharge of about 1/4 A for a period of about 1 hr. Then they pump out the hydrogen and check the voltage the deflector will hold. Typically they'll find that the electron drain current is down by about a factor of 10.

We had a recent experience in the HILAC where the radiation level was very high around the pre-stripper tank at high gradient in the tank. Last Wednesday they let the tank down to air and cleaned it with solvents and sandpaper. There was quite a change, probably close to a factor of 10, in the x-ray level surrounding the tank. I have often wondered if one might clean the surfaces of a linac using this hydrogen scrubbing technique. It seems to me if you had a small setup where on could afford to experiment, that probably all that you would have to do would be to put an auxiliary electrode in it, apply a few hundred volts at 60 cycles, let it down to hydrogen, and run a discharge for a period. Then remove the hydrogen and go back to the voltage level you were at before and measure your x-ray level to see if there is any appreciable change. I suspect that one would want to do it when the tank is fairly dirty and where you have found a significant increase in the x-ray level. This is just a suggestion which might be worth trying. It might be pretty useful to linac people if it works there the way it does in the case of dc electrodes.

RADMER: At what pressure did you suggest operating?

B. SMITH: About 100 μ. Now the theory behind it, which I can't vouch for, is that over a period of time oxides form on the copper surfaces, and when you run the hydrogen discharge, the hydrogen combines with the oxygen and removes the oxide. I don't know whether that's really a valid explanation or not.

RADMER: That does sound reasonable. One thing I didn't point out was that when talking about reasonable values for work functions, magnification factor, etc., in the constants of the radiation intensity vs electron field equations discussed earlier, we use a much lower value for the work function than the actual work function of copper. We did do a careful measurement of copper, treated the same way as we treat drift tube surfaces and found it to have a work function of about 1.5 eV rather than 4.5 eV. This is also the value that works out quite well in the field equations.

B. SMITH: You have to clean your equipment from time to time?

RADMER: Yes. I don't know whether this hydrogen treatment would clean up the surface.

B. SMITH: It might be interesting to find out. If it worked, it would be of use to everyone who runs a linac.

HUBBARD, LRL: I have a comment on Bob Smith's question. At Berkeley a number of years ago we had a cavity like this, and we tried the experiment you are suggesting. It does help.

B. SMITH: How large was the improvement?

HUBBARD: More than a factor of ten in x-ray levels. This was, as you say, with a tank that was not particularly clean to start with. It is not necessary to use hydrogen; most any gas will work. We've tried oxygen, nitrogen, and several others. We ran the glow discharge with the rf itself, however. I think it's well known that a glow discharge is a cleaning process for a surface and I think that's probably what is involved.

RADMER: By "not a clean system," do you possibly mean an oil diffusion pumped system?

HUBBARD: We did it in both oil and mercury pump systems. This was before the advent of vac-ion pumps.

RADMER: Dr. Schmelzer's group at Heidelberg has done an experiment in which they put a very thin coat of oil on a drift tube surface. Under this condition their test cavity produced much higher radiation levels and sparking rates, which is not surprising.

FEATHERSTONE: First, regarding oil: I think it was observed in the original Alvarez machine (and I know it has been repeatedly observed in our machine) that, if the drift tubes are clean and you observe a particular radiation background, then as the months go by and diffusion-pump oil works back into the machine, the radiation level continually rises. We've always ascribed this to an increase in secondary electron emission.

Second: I would like to ask whether the hydrogen scrubbing process is of any advantage to people who are trying to keep the emission current low on stainless-steel electrodes in accelerating columns?

B. SMITH: I have not observed the effect of hydrogen scrubbing on stainless steel electrodes but presume that it would be beneficial here also.

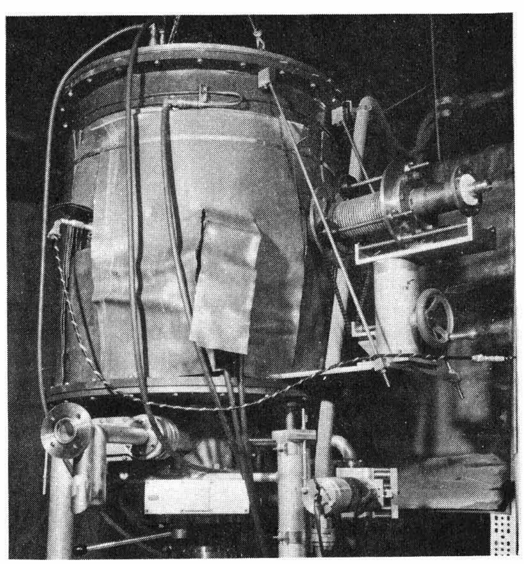

Fig. 1. The 200 MHz sparking cavity.

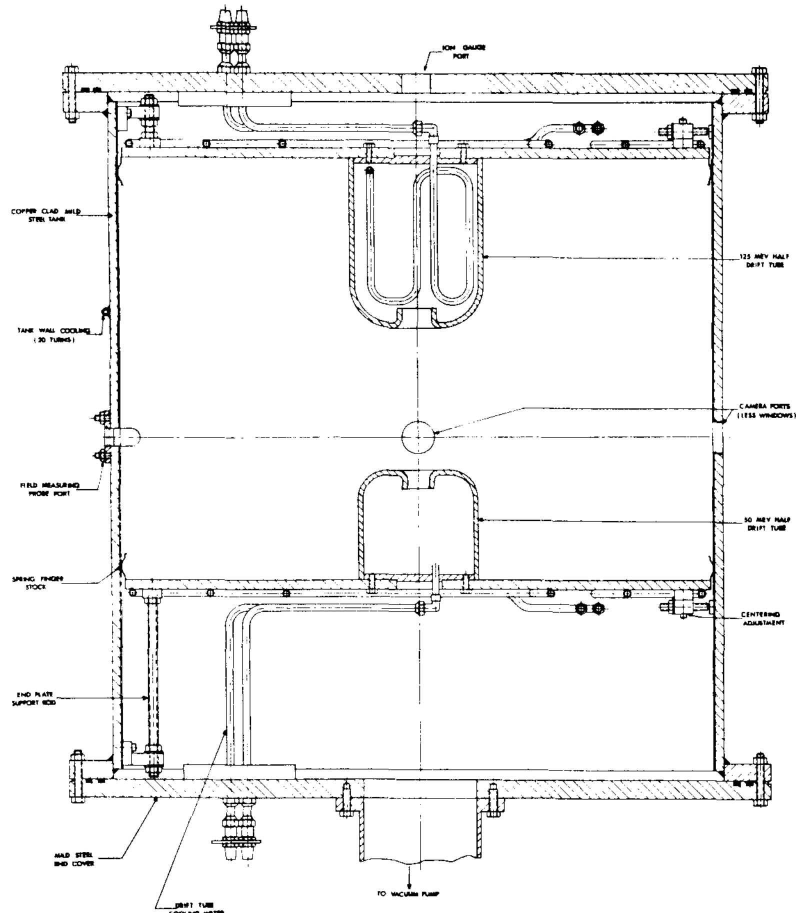

Fig. 2. Section view of sparking cavity with the 50 MeV drift tube (bottom) and the 125 MeV drift tube (top).

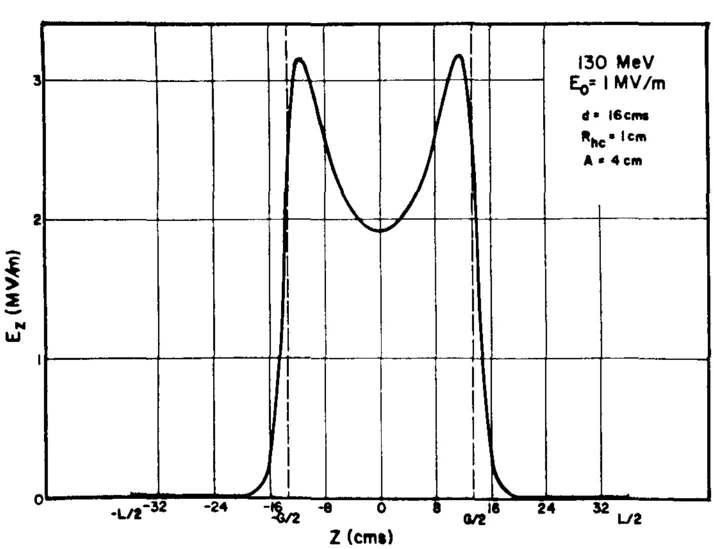

Fig. 3. Field distribution on the axis for 130 MeV geometry.

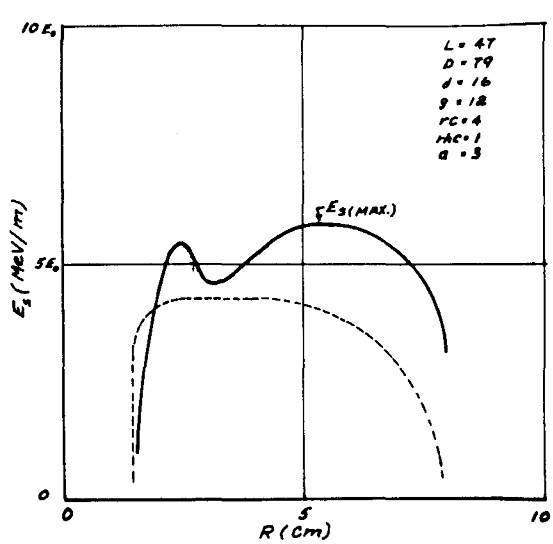

Fig. 4. Surface field of 50 MeV drift tubes.

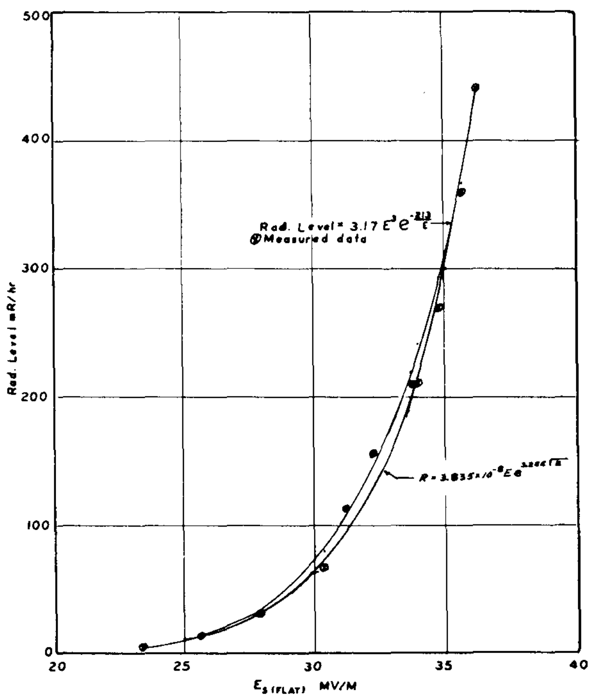

Fig. 5. Radiation level as a function of maximum field (5 MeV configuration).

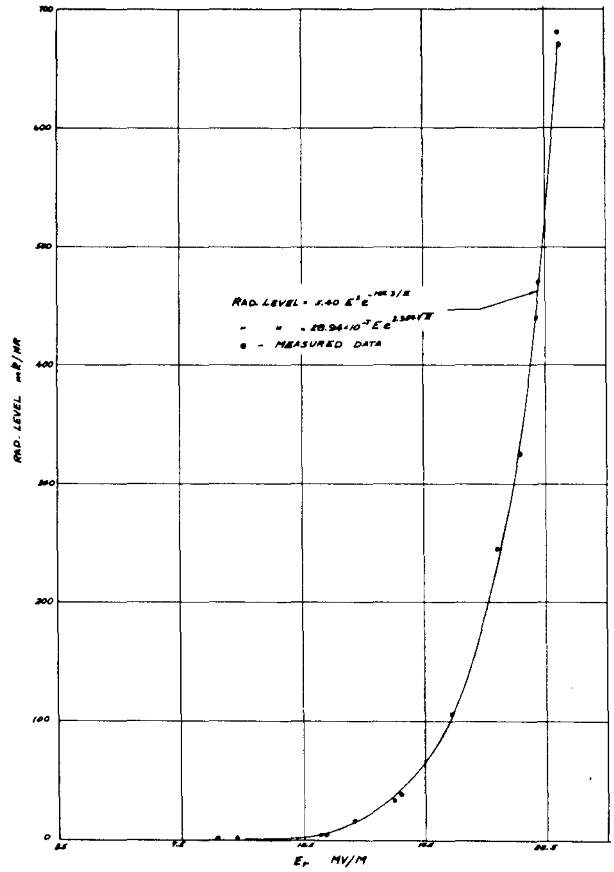

Fig. 6. Radiation level as a function of maximum field (50 MeV configuration).

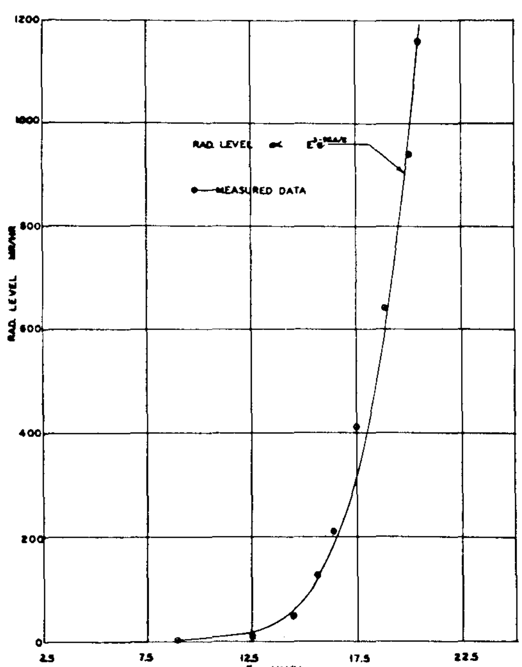

Fig. 7. Radiation level as a function of maximum field (130 MeV configuration).

Figure 8

PEAK OPERATING CONDITIONS FOR
THREE DIFFERENT LINAC UNIT CELLS

	5 MeV	5 MeV	130 MeV
Peak Power	330 KW	328 KW	388 KW
Average Axial Field, E_o	5.34 MV/m	3.93 MV/m	3.53 MV/m
Average Gap Field, E_g	32.0 MV/m	15.4 MV/m	9.30 MV/m
Maximum Surface Field, E_x	38.5 MV/m	23.2 MV/m	20.5 MV/m