THE DEPENDENCE OF TRANSVERSE EMITTANCE GROWTH OF THE QUADRUPOLE FOCUSSING STRENGTH IN THE BROOKHAVEN 200 MEV LINAC*

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Introduction

Transverse emittance growth in bright linac(1) beams have been both observed experimentally and predicted by computer simulations.(2,3) However, for a typical high intensity beam in the Brookhaven 200 MeV linac (4) the beam brightness at injection is such that according to results obtained in earlier computer calculations, which assumed longitudinally and transversely well-matched and ideally bunched beams only a very minor emittance growth of 20-30% should take place. Contradictory to these expectations emittance measurements which were made in the past at injection and at 10 MeV (1) indicated growth factors between 2 and 3. At the time of these measurements the analysis of the data was extremely time consuming and a more extensive study of the emittance growth was prohibited. Since then the emittance measuring device used for these studies has been connected to a PDP-8 computer and the data handling time has been shortened by several orders of magnitude. It therefore became feasible to try to get a better understanding of the observed emittance growth and it was suggested that the growth factor be measured as function of the quadrupole focusing gradients in the first 10 MeV tank.

Measurement

The horizontal and vertical beam emittances were measured at 0.750 MeV immediately in front of tank 1 and at 10 MeV halfway between tank 1 and tank 2. A destructive multi-pickup measuring device was used, the details of which have been reported earlier (5) and which in its computerized version will be described later during this conference.(6)

The beam intensity in front of tank 1 was 150 mA, and both horizontal and vertical emittances were $\sim 5\ \pi$ cm-mrad. A single cavity, 71 cm drift-space buncher was used.

Special care was taken to obtain a matched beam at the beginning of tank 1, since earlier computer calculations (2) had shown this to be important for minimizing emittance blow up. Matching conditions at the beginning of the first linac cell were calculated using a model, that assumed that the beam is a uniformly charged ellipsoid. The calculated emittances were then brought backwards to the place of the 0.750 MeV emittance device. Fig. 1 shows the calculated horizontal and vertical emittances corresponding to 0.8, 1.0 and 1.2 times the normal quadrupole setting in tank 1. It can be ascertained from this figure that in each plane the three matched ellipes are quite similar in eccentricities and orientations and those obtained for the normal quadrupole settings were used as guides for beam matching in all measurements.

The quadrupoles in the 0.750 MeV transport system were adjusted to obtain the desired matching conditions in the measuring device in front of tank 1. Figure 2 shows the measured emittances for $\sim 90\%$ of the beam. It can easily be seen from here that these emittances agree well with the calculated ones of Fig. 1. Emittances were measured at 10 MeV for five different quadrupole gradient levels in the 10 MeV tank corresponding to 0.8, 0.9, 1.0, 1.0 and 1.2 times the design values. Slightly different 10 MeV output currents were recorded for the different quadrupole settings and the measured emittances were normalized to 95 mA obtained for design quadrupole gradients. Figure 3 shows the measured horizontal and vertical emittances for 90% of the beam at the 10 MeV emittance measuring device, obtained with normal quadrupole settings. 10 MeV emittances as function of percentage of beam for the different quadrupole gradients are shown in Fig. 4. Examination of the points in this figure reveals no obvious correlation between emittance areas and quadrupole focusing strength. Emittances lie within $\pm$ 10% of each other for beam percentages between 50 and 90% for which the measuring device has its greatest accuracy. In Fig. 5 the fractional increase in normalized emittance is shown as function of percentage of beam for design quadrupole settings. Average growth factors of 2, obtained in both planes for beam percentages between 50 and 90%, agree fairly closely with results from earlier experiments which were mentioned in the introduction.

Calculations

The calculated matched emittances shown in Fig. 1 together with a distribution in longitudinal phase space obtained from a typical buncher run were taken as input distribution and computer runs were made through tank 1 for quadrupole gradient settings equal to 0.8, 1.0 and 1.2 times their design values. A six dimensional linac motion code (7) taking into account the effects of space charge was used. Figure 6 shows the calculated horizontal and vertical emittances at the place of the 10 MeV emittance measuring device, obtained from a run with design quadrupole gradient values. Good agreement was obtained with the measured emittances shown in Fig. 3.

Rms emittances were calculated as function of drift tube number and are shown in Fig. 7. It can be ascertained from here that the calculated emittances at 10 MeV lie within 25% of each other. Taking into account somewhat different tank transmissions obtained in these runs the growth factors have been normalized to the same output current (91 mA) and are shown below (where ε = normalized emittance).

Quadrupole Setting in "Design Value Units"	$\delta = \dfrac{\varepsilon_{10\ \mathrm{MeV}} - \varepsilon_{0.750\ \mathrm{MeV}}}{\varepsilon_{0.750\ \mathrm{MeV}}}$
0.80	1.1
1.00	1.1
1.20	1.0

*This work was performed under the auspices of the U. S. Atomic Energy Commission

The calculated 10 MeV emittance growth is hence virtually independent of quadrupole focusing strength. However, as can be seen from Fig. 7, a somewhat faster growth rate is obtained with the weakest quadrupole system.

Figure 8 shows the calculated longitudinal and average transverse rms emittances as function of drift tube number. Both emittances have been normalized to the same units. The large decrease in longitudinal emittance in the first part of tank 1 is due to particles that are lost out of the rf bucket. The initial ratio of 10:1 of longitudinal to transverse emittance is reduced to 3:2 at 10 MeV.

Discussion

Both measurements and calculations presented in this work indicate that the transverse emittance growth at 10 MeV is insensitive to ± 20% variation in the strength of the quadrupole system in the 10 MeV tank. These results confirm previous conclusions regarding transverse phase space blow up in bright linac beams.

Earlier computer experiments show that the growth originates in longitudinal-transverse coupling through non-linear space charge forces. It was also found that the transverse emittances W_x and W_y tend to approach the longitudinal emittance W_z provided that $W_z > W_x, W_y$ at injection which generally holds true in a proton linac.

In connection with these findings it was suggested that the upper limit of the transverse emittances is determined by the size of the longitudinal emittance only and not by machine parameters, while the latter would influence the rate of emittance growth. Results obtained in this work point towards the same conclusion.

The somewhat unexpected size of the emittance growth which was observed and calculated for a 95 mA beam in the 200 MeV BNL linac can be explained by the fact that earlier calculations assumed longitudinally matched beams resulting from idealized bunches with longitudinal phase space area about 7 times smaller than those obtained in practice.

Conclusions

Observed and calculated transverse emittance growth of a high intensity beam in the 10 MeV section of the Brookhaven linac shows little dependence on the strength of the transverse focussing there. Efforts to improve the transverse beam quality should be directed towards the design of more intricate buncher schemes resulting in a smaller longitudinal emittance at injection.

Acknowledgment

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References

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DISCUSSION

Teng, NAL: I didn't understand you in the case of the variable phase. Your calculation is for a continuously variable phase, whereas, when you adjust the nine tanks, don't you get a step function?

Chasman: We tilted the first and the second tanks to follow the law which I showed. After the second tank, the change in the field levels is only 2% and less, so that we took the average value at the middle of the tank and tried to set the tank to that value.

Curtis, NAL: I might make one comment: We reduced the gradient of Tank 1, which, of course, reduces the acceptance, and measured the momentum spread for 20 mA with the buncher off at nominal gradient. We then reduced the tank gradient and turned the buncher on to get the same beam current, and the momentum spread went down noticeably as you might expect. Then we looked at the emittance at 200 MeV, and it did not go down. We wondered if it might be because of the coupling.

Ohnuma, NAL: Of course, the objective is to reduce the momentum spread of the beam when it's injected into the AGS, not at the end of the linac. Even if you have a very good momentum spread at the end of the linac, it's of no use if the momentum starts spreading when it goes into the AGS. Now you have a rather long transport from the linac to AGS, I believe. When you manipulate energy spread in this way, do you get the comparable improvement at the injection point of the AGS?

Chasman: Well, we haven't really looked into this yet, but as I said, with the increase in phase spread at the end of the linac I think there's good hope that the further increase in momentum spread due to space-charge effects should decrease.

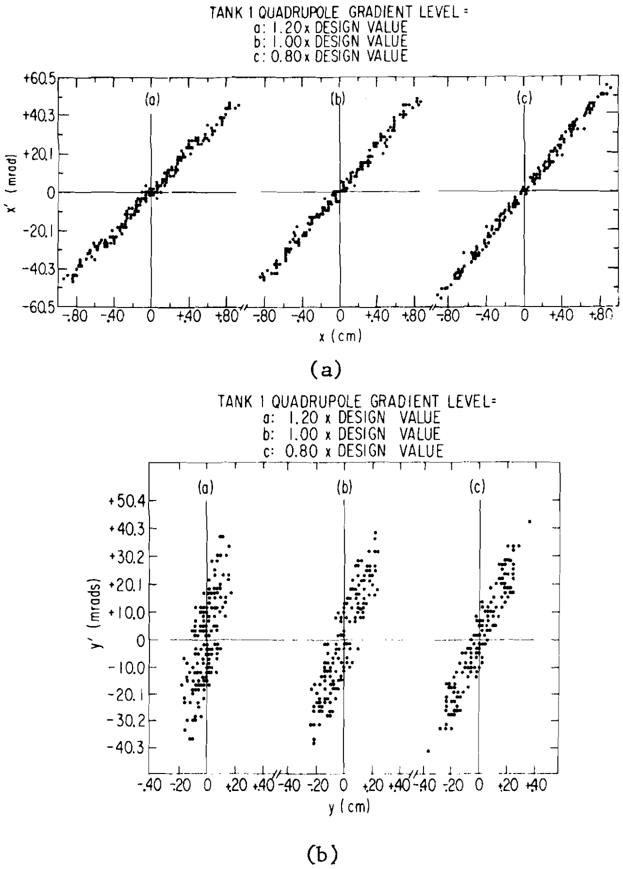

Fig. 1. Calculated matched horizontal (a) and vertical (b) emittance at emittance measuring device in front of linac.

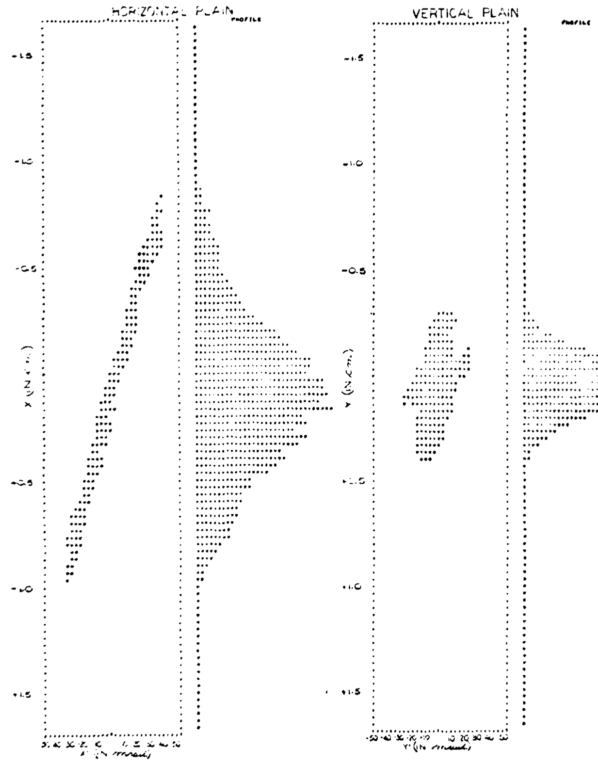

Fig. 2. Measured 0.750 MeV emittance

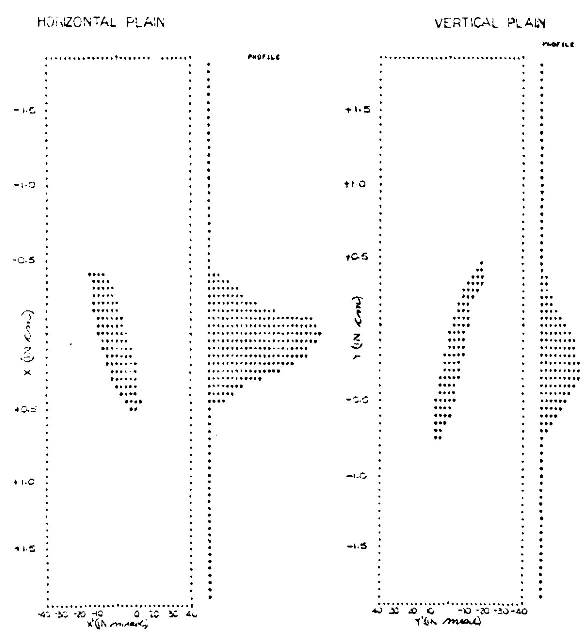

Fig. 3. Measured 10 MeV emittance.

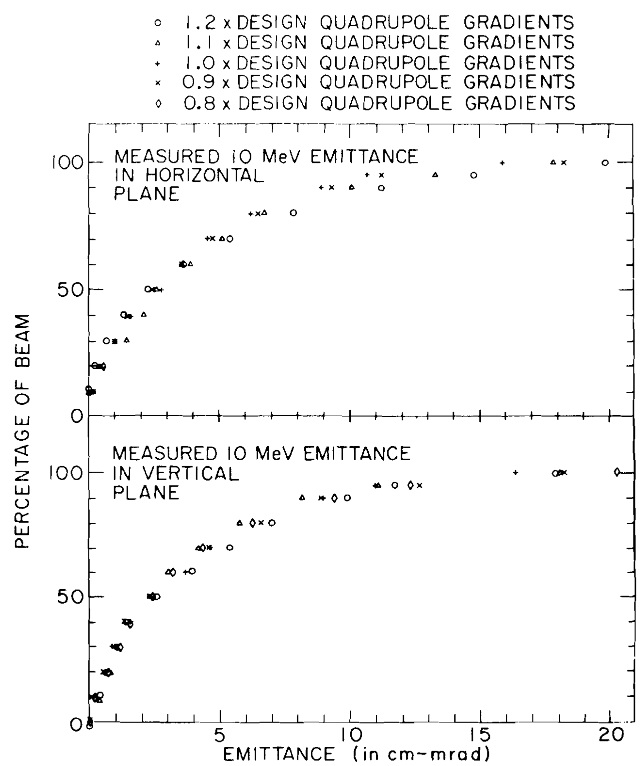

Fig. 4. Measured 10 MeV emittance areas as a function of percentage of beam for different quadrupole gradient levels in 10 MeV tank.

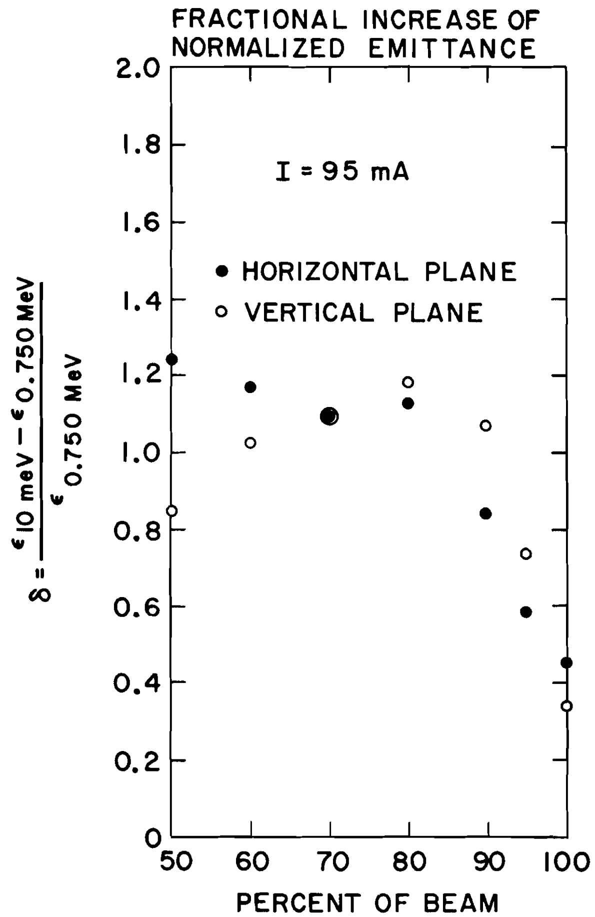

Fig. 5. Measured fractional increase in normalized emittance for design quadrupole gradient level in 10 MeV tank.

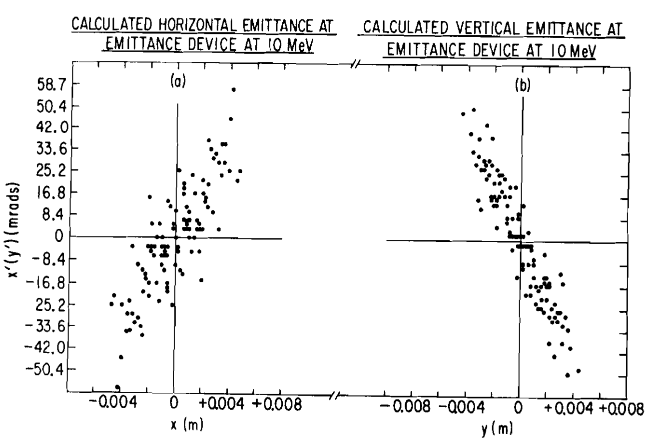

Fig. 6. Calculated 10 MeV emittance at 10 MeV emittance measuring device.

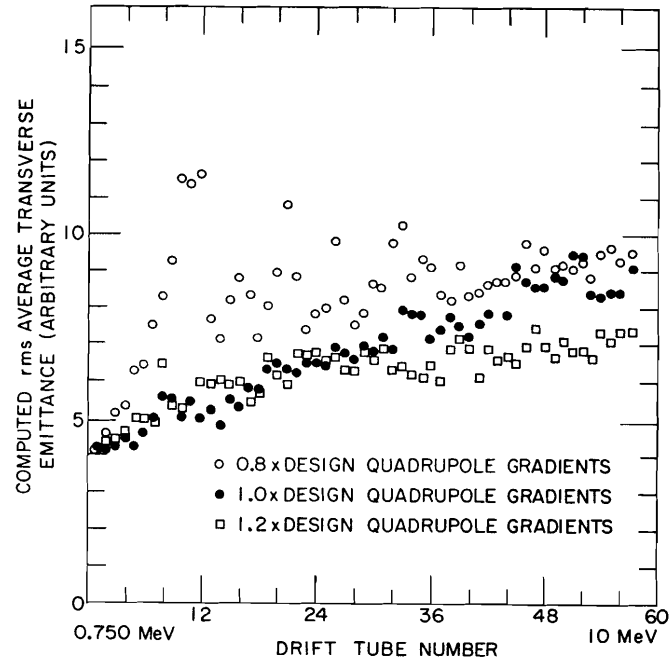

Fig. 7. Calculated rms average transverse emittance area as function of drift tube number for different quadrupole gradient levels in 10 MeV tank.

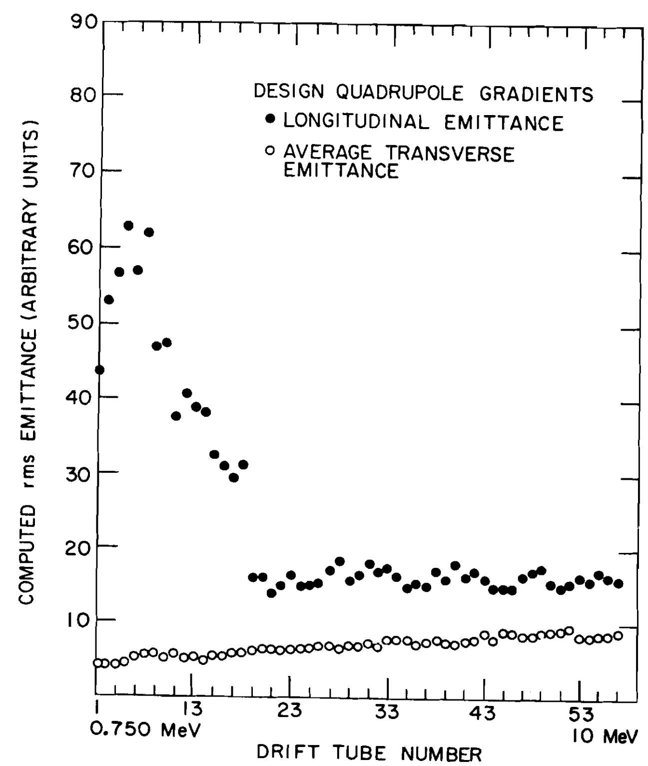

Fig. 8. Calculated rms longitudinal and average transverse emittance as function of drift tube number for design quadrupole gradient level in 10 MeV tank.