

A STUDY OF THE VARIATION OF MAXIMUM BEAM SIZE WITH QUADRUPOLE GRADIENT IN THE FMIT DRIFT TUBE LINAC*

G. P. Boicourt and R. A. Jameson Los Alamos National Laboratory
Los Alamos, NM 87545

Summary

The sensitivity of maximum beam size to input mismatch is studied as a function of quadrupole gradient in a short, high-current, drift-tube linac (DTL), for two prescriptions: constant phase advance with constant filling factor; and constant strength with constant-length quads. Numerical study using PARMILA shows that the choice of quadrupole strength that minimizes the maximum transverse size of the matched beam through subsequent cells of the linac tends to be most sensitive to input mismatch. However, gradients exist nearby that result in almost-small beams over a suitably broad range of mismatch. The study was used to choose the initial gradient for the DTL portion of the Fusion Material Irradiation Test (FMIT) linac. The matching required across quad groups is also discussed.

Introduction

Beam spill must be kept to very low levels in the FMIT deuteron accelerator. This has led to a strong machine-design effort directed toward keeping the maximum beam size observable in computer simulation studies within about 60% of the drift-tube linac bore (neglecting scattering, recombination, and particles outside the theoretical acceptance). Among suggestions for reaching this objective was that of using a constant-length, constant-strength (cl-cs) quadrupole focusing system. This reduces the beam size as the beam proceeds through the linac; on the stability chart, Fig. 1, the operating line would cut across the lines of constant maximum beam size in the

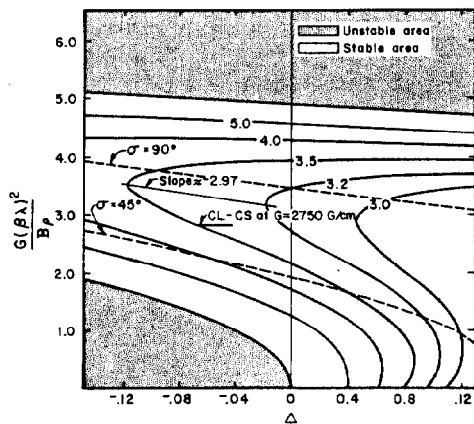


Fig. 1. Alternating-gradient focusing-system stability diagram. The slope of the line shown connecting contours of $\beta_{cs+}/\beta\lambda = 3.2$ and 3.5 has a slope of -2.97 . The operating region for a 17-cell linac with constant-length, constant-strength quadrupoles, with gradient 2750 G/cm, is shown.

direction of smaller transverse beam size as the beam accelerates.¹ We argued that this would, in some degree, counteract the effects that mechanical errors

and emittance growth have on the increase of the maximum beam radius. Note that, for purposes of beam spill, the maximum radial excursion of any beam particle is the important quantity, and thus our problem was to minimize the maximum beam size rather than the rms size, or some other quantity.

The relatively high current in the FMIT linac (100 mA), with the accompanying space-charge effects, made the theoretical choice of the quadrupole operating gradient difficult, because present theory cannot predict maximum beam size. Moreover, we had to be sure that our final choice was stable, with respect to the range of expected possible mismatch of the input beam (we assume the beam radius will not be wrong by more than $\sim \pm 20\%$). We decided to attack the problem by a numerical study using PARMILA.²

Method

We decided to examine both the cl-cs concept and a more standard quadrupole law over the initial 17 cells of the FMIT Alvarez section. As a measure of beam size, the maximum of the maximum radii in the 17 cells was chosen. This value, averaged over a number of runs using different sets of input particles with different randomly chosen coordinates, provides a measure of performance that we believe is acceptable. We have shown³ that this measure can be described by an extreme value distribution and that the average is very close to the median of this distribution.

PARMILA provides, as a standard condition, quadrupoles with length given by $l_q = \epsilon\beta\lambda$, where ϵ is a constant filling fraction. The gradients are determined by the equation

$$\theta^2 = C_1 \Delta + C_2 \quad (1)$$

where

$$\theta^2 = \frac{G(B\lambda)^2}{B\rho} \quad \text{and} \quad \Delta = \frac{\pi E_0 T \lambda \sin \varphi_s - 15 I \beta \lambda^3 \left(\frac{3b-a}{a^2 b^2}\right)}{W_0 B_Y^3}$$

The quantities θ^2 and Δ are the variables of the ordinate and abscissa of one common form of the Smith-Gluckstern stability chart.⁴ As a standard quadrupole law, ϵ was chosen as $1/2$ and the slope C_1 was set equal to -2.97 . This latter value corresponds to a constant phase-advance line on the focusing-system stability chart (see Fig. 1) parallel to the "valley", at the center of the chart, formed by the contours of constant $\beta_{cs+}/\beta\lambda$. The initial gradient then could be set by the selection of C_2 . For the cl-cs case, the length was chosen as $1/2$ the cell length of the initial cell, and the initial (and following) gradients were set directly.

The particle input to the DTL was uniform in four-dimensional transverse phase space, and uniform in the φ - w plane. Particles were started at the center of the input quad (start of cell 1). The initial quadrupole of the DTL was focusing in the x plane.

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The procedure for a given input-quad strength was first to find the $\beta_{CS,x}$ and $\beta_{CS,y}$ that provide a matched beam to the linac. The Courant-Snyder α 's were always taken as zero. In the longitudinal plane, $\Delta\phi = 35^\circ$ and $\Delta E = 0.15$ MeV were used throughout. Next a set of runs (usually 10) was made, with statistically different input particle distributions, to find \bar{r}_{max} . This was followed by more sets of runs with varying degrees of mismatch in the β_{CS} 's.

Results

The beam size is quite insensitive to the initial β_{CS} in the focusing plane. Comparisons of the gradient-strength effect on the beam size were obtained by graphing the results of sets of runs made with the larger β_{CS} fixed at its matched value.

Figure 2 shows the results for five constant zero-current phase-advance cases; the highest to lowest gradients correspond to 93° , 80° , 71° , 64° , and 57° , respectively. We see that roughly the same

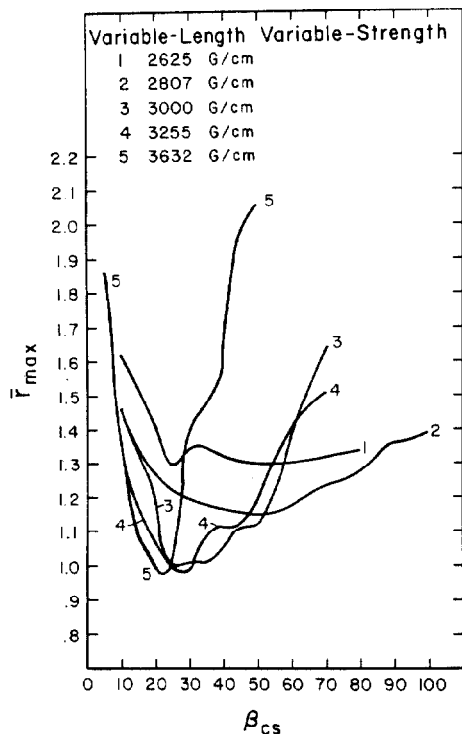


Fig. 2. Curves of \bar{r}_{max} vs β_{CS} for different initial gradients obtained using a variable-length, variable-strength law, with stability-diagram slope -2.97 . Beam current = 100 mA.

minimum beam size is achieved for the three highest phase advances; however, the region of mismatch over which the beam is close to the minimum size decreases as the gradient increases. More insensitivity to mismatch is obtained for 2807 G/cm and 2625 G/cm, but the beam size for a matched input has increased 20% and 30%, respectively.

There is, of course, an expected increase in maximum beam envelope because of a mismatch, given by the square root of the ratio of actual β_{CS} to the matched β_{CS} .

The variations seen here are less than expected, except for the high β_{CS} side of the 93° curve, where it is more, possibly because the parametric resonance with the structure period is excited. The locus of the minimum \bar{r}_{max} for the matched cases might be expected to be a vertical line on Fig. 1 at the appropriate Δ ; the variation for the range of phase advances studied here would be only about 10%. We have not yet determined why the \bar{r}_{max} 's for curves 4 and 5 are so much larger than expected.

Figure 3 gives the results for the same set of input gradients when a cl-cs law is used. The minimum beam size is now achieved for 3255 G/cm, but again, the region of allowed mismatch for this gradient is narrow.*

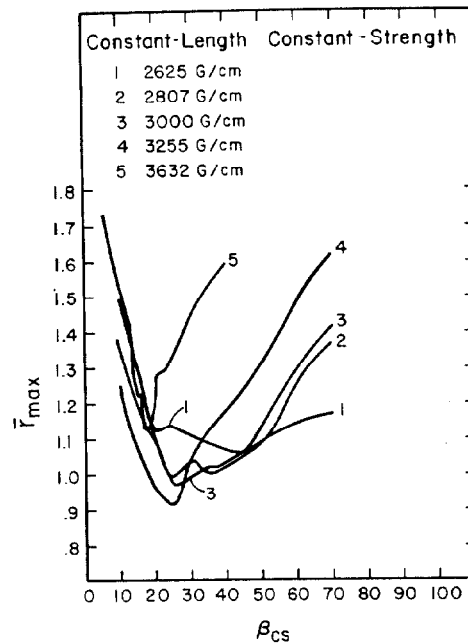


Fig. 3. Curves of \bar{r}_{max} vs β_{CS} for different gradients. These are obtained using constant-length, constant-strength quadrupoles. Beam current = 100 mA.

Examination shows that the cl-cs law results in a smaller beam with a lower gradient, and in less sensitivity to input matching. It seems that a gradient between curves 1 and 2 in Fig. 3 is a good choice.

Figure 4 shows results for an initial gradient of 2750 G/cm. Curve 1 shows a beam size about 10% smaller for a cl-cs quadrupole law than curve 2, which is for the same initial gradient, but uses the law of Eq. (1), with slope -2.97 . Also shown is the curve for the cl-cs law, when the expected alignment errors are included in the calculation. The dashed lines show the expected maximum possible extent of the input mismatch ($\pm 40\%$ in β_{CS}).

Application to the FMIT Accelerator

It is not desirable to use a single type of quadrupole magnet throughout the drift-tube portion

*In Figs. 2 and 3 the points were computed at β_{CS} increments from 1 to 10, with the finer increments in the regions of the minima.

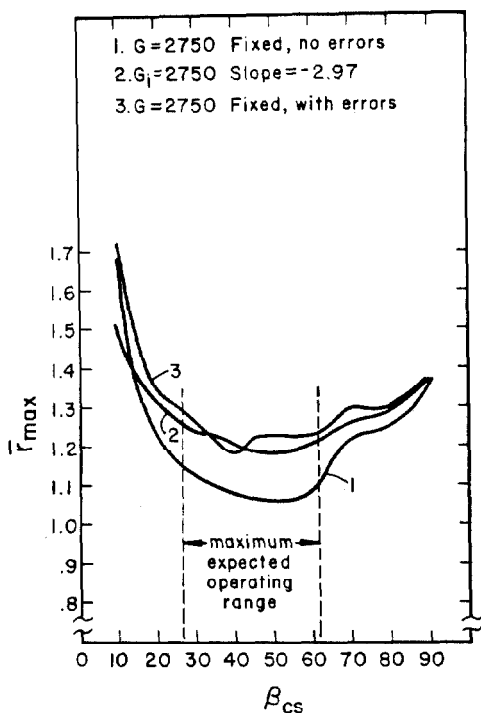


Fig. 4. Comparison of \bar{r}_{max} obtained for cl-cs (Curve 1) and vl-vs (Curve 2) laws for initial gradient $G = 2750$ G/cm. Curve 3 is for cl-cs with inclusion of errors. Beam current = 100 mA. Note change of scale.

of the FMIT linac, because the bore diameter changes from 5 cm to 6 cm to 8 cm; however, it is feasible to use a single quad type for each bore size. Experience has shown that matching is usually required when a change in quad types occurs.

PARMILA runs were made, using three sets of cl-cs quads. We found that detailed matching across the quad transitions was unnecessary, provided the strengths of the downstream quads were chosen properly. To choose the proper gradients, it only was necessary to make a series of runs using the already-determined upstream gradients, while varying the strength of the next quad group. The strength chosen for the group was the one that produced the best beam, based on smooth fit at the quad transition and smallness of beam.

The final choice of gradients seems to have the desired property of maintaining the maximum beam radius at an acceptable size, according to the criterion stated above.

Summary

The use of sets of cl-cs quadrupoles in the FMIT linac has resulted in smaller beam size than would result from the use of a more usual tapering law. The required gradients are also lower. The small beam size is maintained over a $\pm 40\%$ range of transverse mismatch.

References

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