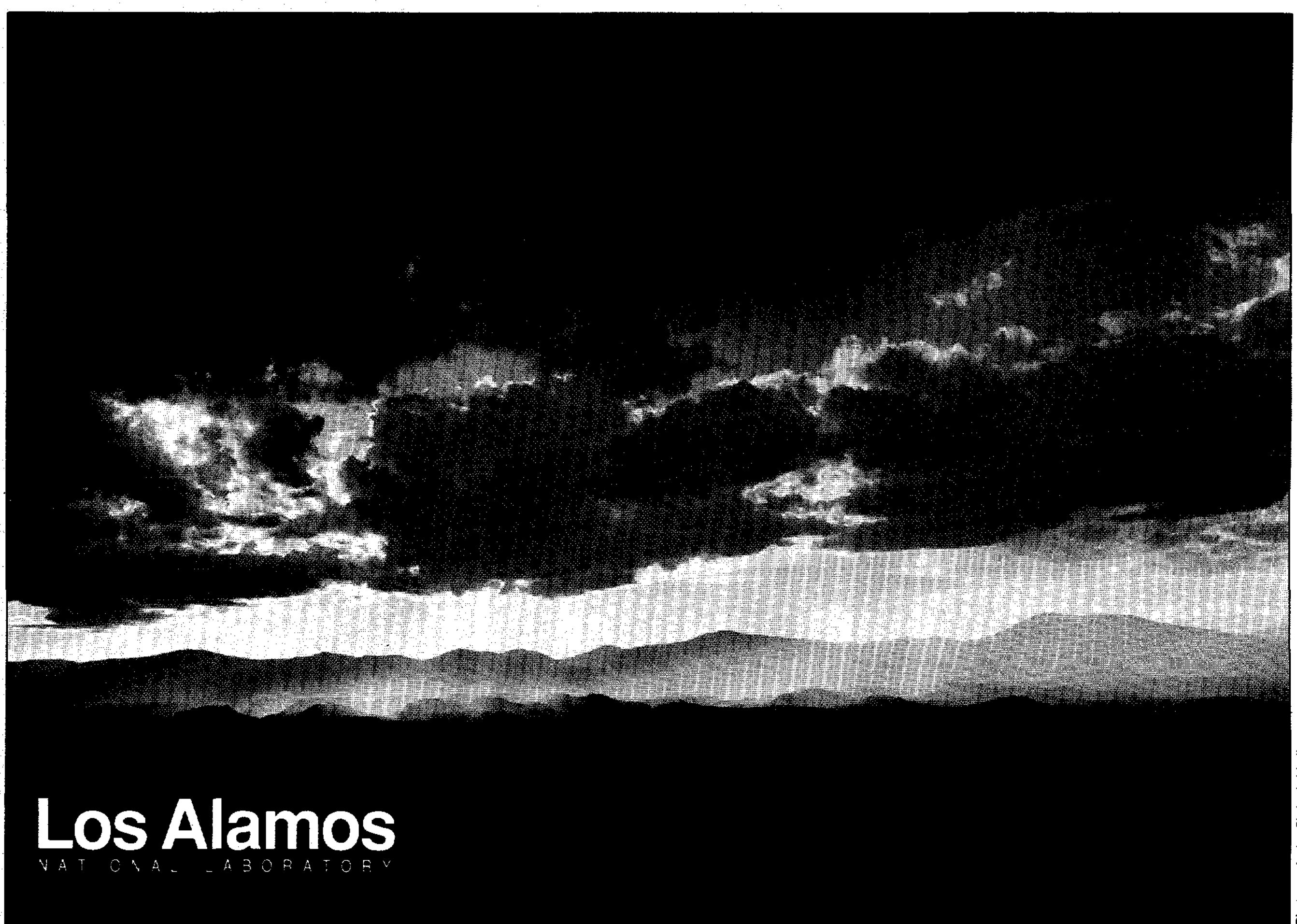
Preprint LA-UR-98-3372

Title: ERROR STUDIES FOR SNS LINAC

Author(s): Kenneth R. Crandall TechSource, Inc.

Submitted To: INFORMAL DISTRIBUTION / INTERNAL AND EXTERNAL



Photograph: by Chris J. Lindberg

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Error Studies for SNS Linac
Part I: Transverse Errors

K. Crandall, TechSource, Inc.

Technique used in this error study

The results reported here were produced using the program PARTREX, which follows the center of the beam in the same way that PARMILA does, but represents the beam by a six-dimensional ellipsoid, as does TRACE. The error studies are done by making many (typically 100) runs for a specified set of error tolerances. In each run, the individual errors are chosen at random within the tolerances specified. At the center of every quadrupole, beam characteristics such as the location of the beam center and the maximum radius to the edge of the beam are noted. At some point along the structure being studied, each of these values will reach its maximum, and these maximum values get saved at each run. After all the runs are made, one can sort the various quantities and determine a probability distribution for each. For example, one could see that the maximum displacement of the beam center was below 3 mm in 80% of the runs. One would then imply that, for the error tolerances specified, there was an 80% probability that the beam center would not be displaced by more than 3 mm from the linac axis, and a 20% probability that it would be displaced by more than 3 mm.

The distance from the linac axis to the edge of the beam depends on the coordinates of the beam center and on the size and orientation of the elliptical cross-section of the beam in the x-y plane. In the beam dynamics calculation, the size of the beam ellipsoid is $\sqrt{5}$ times the rms size. But for purposes of doing error studies, one can specify a "safety factor" by which to multiply the rms beam size. For example, specifying a 3 would mean that the edge of the beam is considered to be at 3 rms widths of the beam. Knowing where the edge of the beam is located, and knowing the aperture radius, PARTREX calculates a "filling factor", which is defined as the radius at the beam edge divided by the radius of the aperture. If this filling factor is unity, this implies that the beam is just scraping at the 3-sigma level, for example (if 3 has been specified). Larger values mean that more of the beam will be scraping.

In doing error studies, it is informative to look at the effect of each type of error individually. This allows one to set a reasonable tolerance for each error or, if the desired tolerance is unattainable, to determine how often corrective measures (such as steering) will be needed. It also allows one to compare the effects of the various errors and to judge their relative importance. After each error type is studied alone, then one can select a tolerance for each type and make runs with all the errors included, to see their cumulative effect.

Although the beam center sees all the nonlinear forces (if any), the beam ellipsoid in PARTREX sees only linear forces, including space charge. So the only emittance growth is 1) that estimated in going through an rf gap; and 2) the *effective* emittance growth caused by quad rotations, which mix the x- and y-motions. There is no emittance growth caused by a mismatch, for example. The rationale in ignoring these effects is that, if the tolerances are large enough to cause these problems, the tolerances are too large and had better be reduced or corrected. After error tolerances are set using these linear techniques, it would be useful to make a bunch of runs with PARMILA using these error tolerances.

SNS linac configuration

The SNS linac consist of a radio-frequency quadrupole (RFQ), a drift-tube linac (DTL), a coupled-cavity drift-tube linac (CCDTL) and a coupled-cavity linac (CCL). The RFQ and DTL are operated at 402.5 MHz; the CCDTL and CCL are operated at 805 MHz. Between the RFQ and DTL is a medium-energy beam-transport system (MEBT). This error study is concerned with the DTL, CCDTL and CCL, and each will be analyzed separately. In fact, the CCL is divided into two sections, and each of these will be analyzed separately.

The types of errors considered here are those that affect the transverse characteristics of the beam. The errors that cause the beam center to be displaced from the linac axis are quad displacements and quad tilts. The errors that cause mismatches are quad gradient errors and quad rotations (roll).

DTL: 2.5 - 20.3 MeV

Quadrupole misalignments

In Fig. 1 are shown three probability distribution curves of the maximum displacement of the beam center from the linac axis. Each of these curves was produced by making 100 runs through the DTL when the quads were randomly displaced from the axis within a specified tolerance. The displacement tolerances that generated the three curves are 0.002", 0.004" and 0.006". The ordinate of the graph is the fraction of the total number of runs in which the beam displacement was less than or equal to the abscissa. For example, the curve labeled *b* in Fig. 1, produced when the error tolerance on quad displacements was 0.004", shows that in half of the 100 runs the maximum displacement of the beam center was less than about 0.15 cm, and that in about 98% of the runs the maximum beam center displacement was less than about 0.30 cm. This says that, if the uncertainty in the quad alignments is 0.004", there is a high probability that the beam center will be displaced from the axis by no more than 0.3 cm throughout the DTL. Curve *c* shows that a 0.006" tolerance might produce a maximum beam displacement of about 0.45 cm, although the probability of doing so is small (about 2%). Since there is no easy way to steer the beam back on axis in the DTL, these curves would indicate that the tolerance on quad displacements should be no more than 0.004", if possible.

Figure 2 shows two probability distribution curves of the maximum displacement of the beam center when the quads are randomly tilted in both x- and y-, with tolerances of 1 degree and 5 degrees. The curves are plotted on the same scale as in Fig. 1 for comparison. One can see that a random tilt with a 5-degree tolerance has about the same effect as a random displacement with a 0.002" tolerance, but there is no need to be deliberately sloppy, and a 1-degree tilt is relatively easy to accomplish.

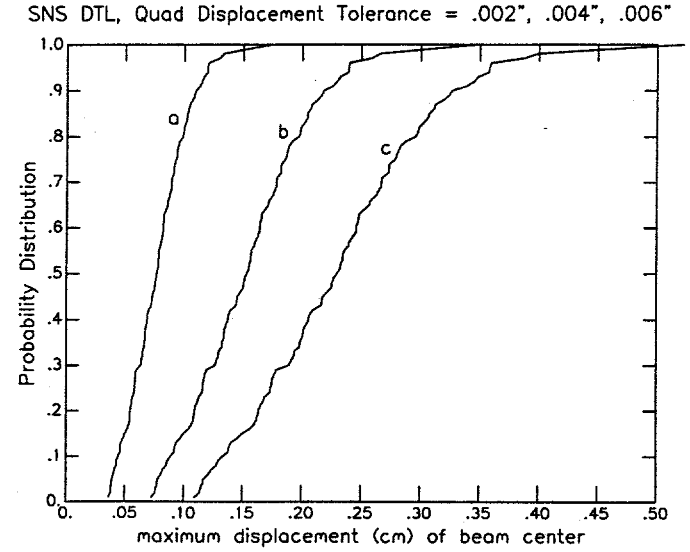


Fig. 1. Probability distributions for the maximum displacement of the beam center in the DTL, produced when the tolerance on the random displacements of the quads were 0.002" (a), 0.004" (b), and 0.006" (c).

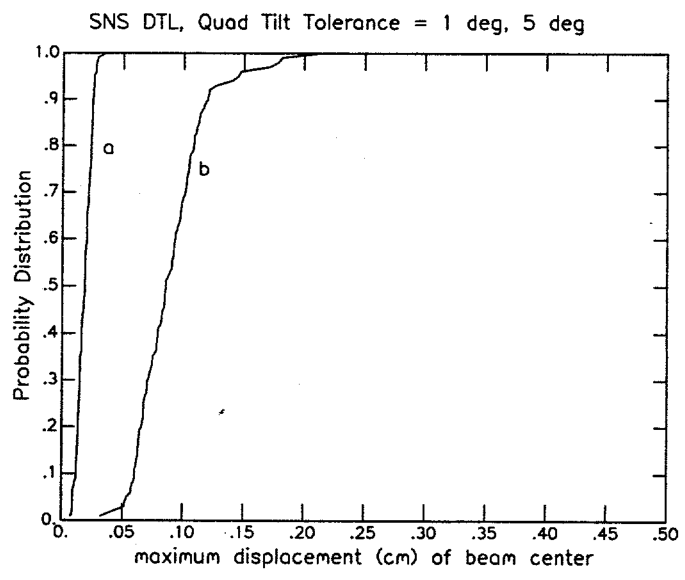


Fig. 2. Probability distributions for the maximum displacement of the beam center in the DTL, produced when the tolerance on the random tilts of the quads were 1 degree (a) and 5 degrees (b).

Quad gradient errors

The tolerance on quadrupole-gradient errors is given by a percentage deviation from its design value The tolerance on quad gradient errors referred to here is the tolerance on the *random errors* in the quad gradients. If all the gradients were a little higher or a little lower than their design values, or if they were ramped a little more or less, it wouldn't have much of an effect. But random errors can cause the beam to become mismatched, and this can cause problems. Shown in Fig. 3 below is the probability distribution of the filling factor (at 3 rms widths) produced by random quadrupole gradients with error tolerances of 0.5%, 1% and 2%. One can see that a tolerance of 0.5% does not have much effect, and gradients can be determined better than that.

What if the beam extends beyond 3 rms widths? Since there were no errors that cause the beam center to be displaced from the linac axis, the results shown in Fig. 3 can be scaled to whatever safety margin one wants to use. For example, if one thinks that 5 rms widths is more reasonable, simply multiply the abscissa by 5/3.

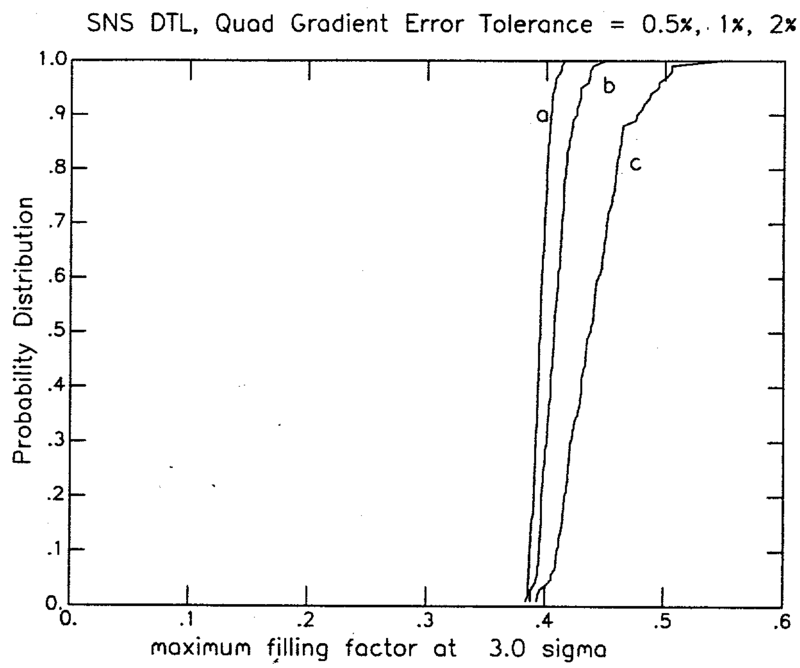


Fig. 3. Probability distributions for the maximum filling-factor exceeding the abscissa when the quad strength error tolerances are 0.5% (a); 1% (b); and 2% (c).

Quad rotation errors

If the ***magnetic axes*** of the quads are rotated about the longitudinal axis, this causes a mixing of the x- and y-motions of the beam particles. A sequence of quads having random rotations can cause an increase in the *effective emittances* in the x- and y-planes, and can make the beam larger in these directions. In Fig. 4 are shown probability distributions for the effective emittance (rms, normalized) in the x-x' phase plane obtained when the error tolerances on the quad rotations were 0.25, 0.5, and 1.0 degree. These curves indicate that a tolerance of 0.25 degrees should be adequate. The limit is probably determined by how well the magnetic axes can be determined; how well the magnetic axes coincide with the geometric axes of the quad.

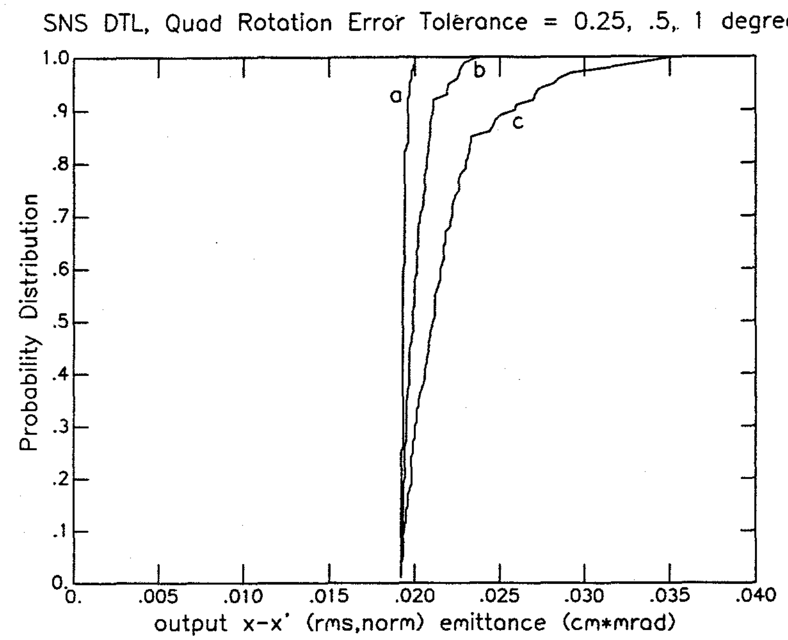


Fig. 4. Probability distributions for the output effective emittance of the beam when the quad rotation error tolerances are 0.25 (a); 0.5 (b); and 1.0 (c) degree.

CCDTL: 20.3 - 94.4 MeV

Quadrupole displacements

The effect of a quad displacement tolerance of 0.005" is shown by the probability distribution curve [(a) in Fig. 5] of the maximum displacement of the beam center in the CCDTL. (A 0.005" tolerance is a reasonable value, and one assumed for the quad displacement in the APT project.) For this calculation, the input beam was assumed to be on axis, which will definitely not be the case because of quad misalignments in the DTL. So steering corrections are definitely called for. Steering is done in pairs: that is, the beam is steered at two locations to bring the beam back on axis at two downstream beam position monitors (BPM). Steering may be done either by adding steering coils to the quadrupoles or by displacing quadrupoles. Steering is more effective (less is required) if done in the plane in which the quadrupole is focusing. The effect of one steering algorithm is shown by curve (b) in Fig. 5. In this algorithm, BPM pairs were separated by 11 quadrupoles (5.5 focusing periods), and steering in the x-plane was done in the nearest two upstream positive (horizontally-focusing) quads, and steering in the y-plane was done in the nearest two upstream negative (vertically-focusing) quads. For example, the quad following the first CCDTL cavity is a positive quad. If we call this quad #1, then quad #2 is a negative quad, and all positive quads are odd-numbered and all negative quads are even-numbered. So x-steering is done in quads 1 and 3, and y-steering is done in quads 2 and 4. The BPMs are located in quads 4 and 6, and measure both x- and y-displacements. The next set of BPMs are located in quads 15 and 17; the x-steering is done in quads 13 and 15; the y-steering is done in quads 12 and 14. And so on throughout the CCDTL. There are nine such steering sets in the CCDTL.

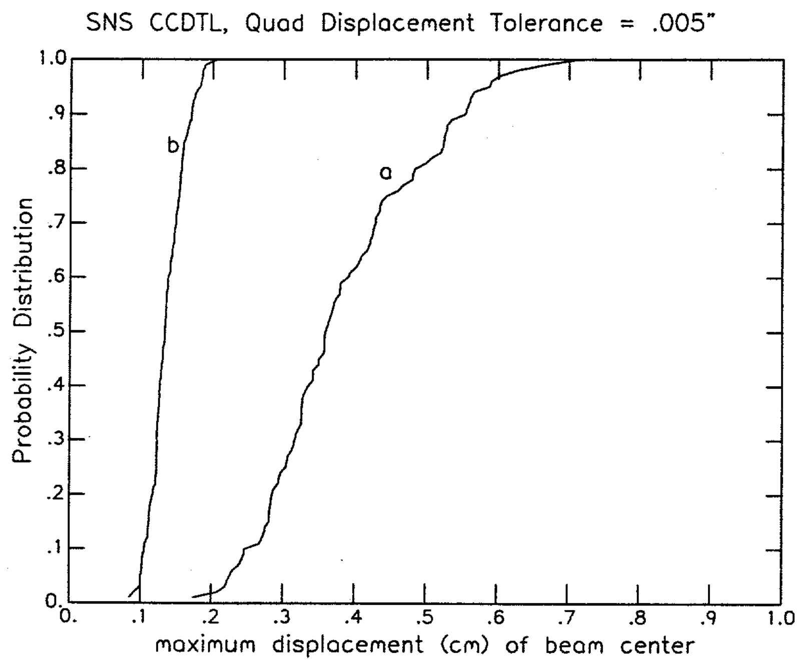


Fig. 5. Probability distribution of the maximum displacement of the beam center in the CCDTL when the tolerance on the random displacements of the quads was).005". Curve (a) is with no steering corrections; curve (b) has steering corrections.

One can see that this steering scheme has a high probability of keeping the beam center within 2 mm from the linac axis. The beam from the DTL may be displaced by more than 2 mm, but the first steering set should bring the beam back on axis. The errors in the BPM readings were not included in the above calculation. Because of the BPM errors, the beam will not be brought back exactly on axis, the beam oscillation will be increased slightly, and slightly more steering will be required. The net effect is to move curve (b) slightly to the right.

Histograms of the amount of steering required in the 100 runs are shown in Fig. 6. All of the quads in the CCDTL are 3 cm long and have gradients of about 7400 gauss, so a steering strength of 1000 G cm would be achieved by displacing a quad by about 0.045 cm, so the steering could be done by displacing the quads by a fraction of 1 mm.

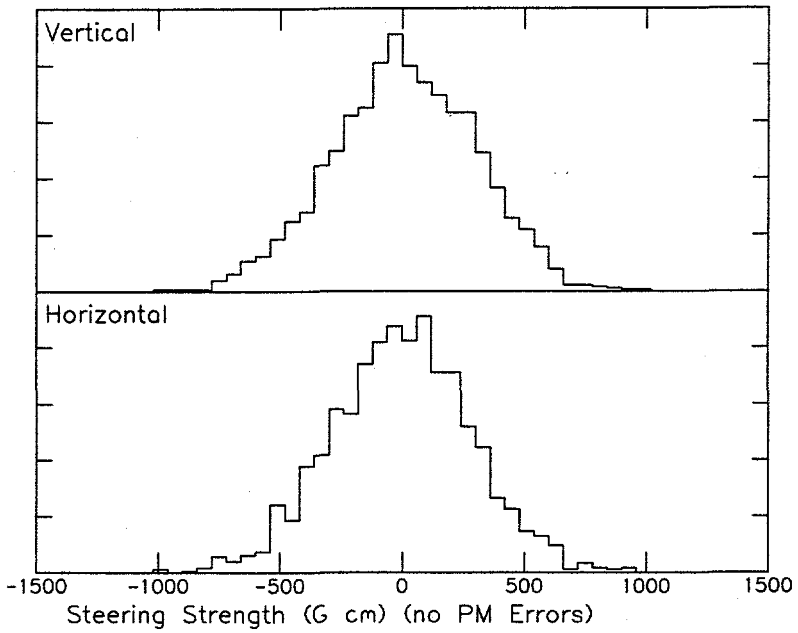


Fig. 6. Histograms of steering strengths used in the 100 runs.

Quadrupole gradient errors

Because the bore radius changes along the CCDTL, rather than showing probability distributions curves of the filling-factor it is probably more instructive to show probability distributions of the maximum radius of the beam. These are shown in Fig. 7 for gradient-error tolerances of 0.5% and 1%. One can see that the 0.5% tolerance has a high probability of having very little effect on the maximum beam size, while a 1% tolerance can cause some increase in the maximum beam size, indicating that a small mismatch is developing.

Quadrupole rotation errors

The effects of 0.25, 0.5, 0.75 and 1 degree tolerances on quad rotation (about its longitudinal axis) are shown in Fig. 8. One can see that 0.25 degrees has very little effect, while a 1-degree tolerance has a noticeable effect. So the tolerance should be 0.25 degrees, just as in the DTL.

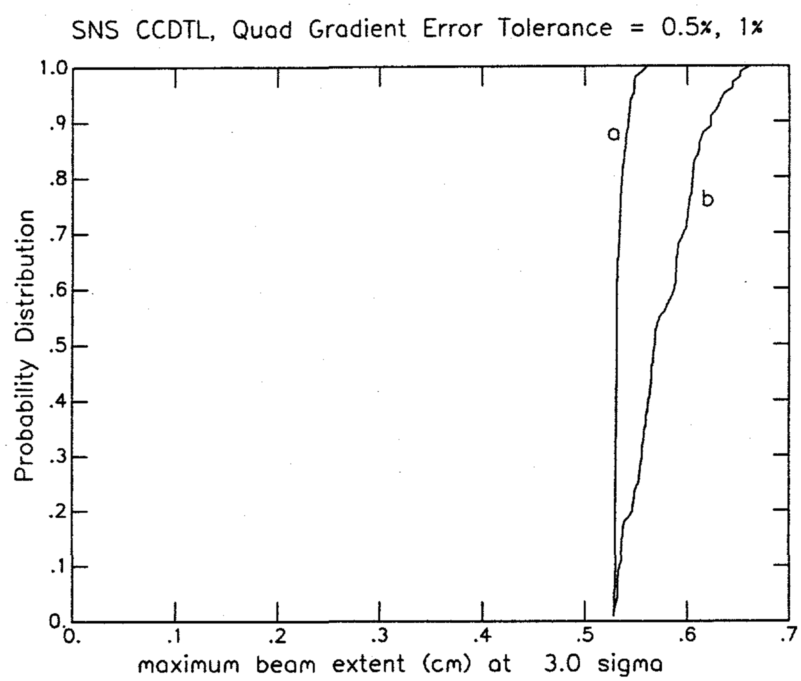


Fig. 7. Probability distributions of the maximum beam extent produced by quad gradient error tolerances of 0.5% (a) and 1% (b).

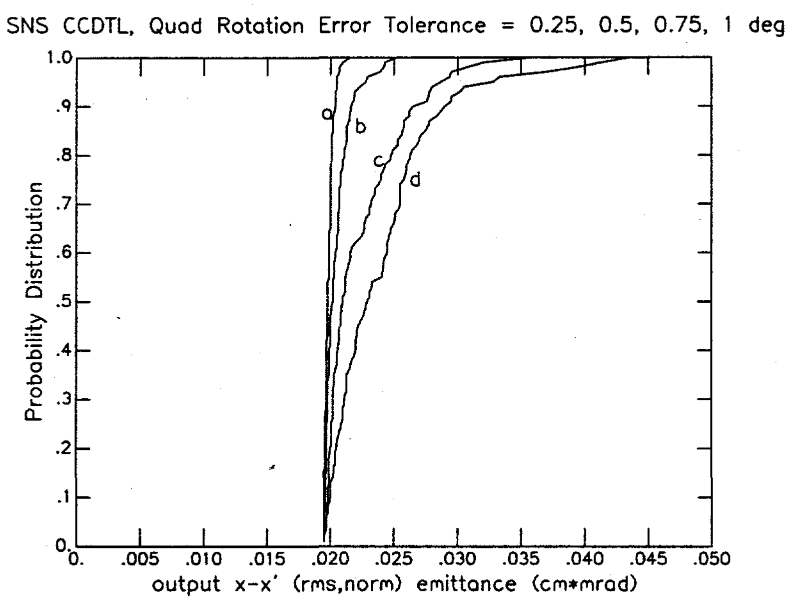


Fig. 8. Probability distributions of the output *effective* emittance in the x-x' plane caused by quad rotation error tolerances of 0.25 (a); 0.5 (b); 0.75 (c); and 1.0 degree (d).

CCL1: 94.4 - 165.7 MeV

Quadrupole displacements

The effects of a quad displacement tolerance of 0.005" and 0.010" are shown in Fig. 9 by the probability distribution curves of the maximum displacement of the beam center in the CCL1. A 0.005" tolerance should be the goal; the results for a 0.010" tolerance are given for a comparison. In Fig. 10 are shown these same curves when steering is done every 5.5 focusing periods (11 quads). There are 44 quads in this section of the linac, so there are 4 steering sets. Steering is done at the beginning of the section to get the beam emerging from the CCDTL back on axis. The same scales are used in Figs. 9 and 10 to emphasize the effects of steering.

Histograms of the steering strengths required when the quad displacement tolerances are 0.005" and 0.010" are shown in Figs. 11 and 12, respectively. One can see that the 0.010" tolerances require twice as much steering strength, as would be expected.

Quadrupole gradient errors

Again, because the bore radius changes along the CCL1, rather than showing probability distributions curves of the filling-factor, probability distributions of the maximum radius of the beam are shown in Fig. 13 for gradient-error tolerances of 0.25%, 0.5% and 1%. There is not a big difference between these curves, but APT people have maintained that 0.25% is a reasonable objective for a tolerance on quad gradient errors.

Quadrupole rotation errors

The effects of 0.25, 0.5 and 1 degree tolerances on quad rotation (about its longitudinal axis) are shown in Fig. 14. The tolerance should be 0.25 degrees.

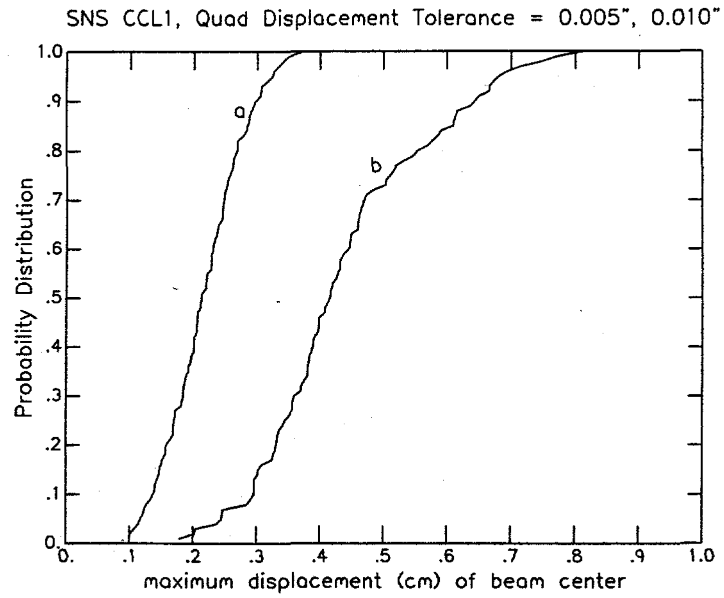


Fig. 9. Probability distribution of the maximum displacement of the beam center in the CCL1 when the tolerance on the random displacements of the quads was 0.005" (a) and 0.010" (b).

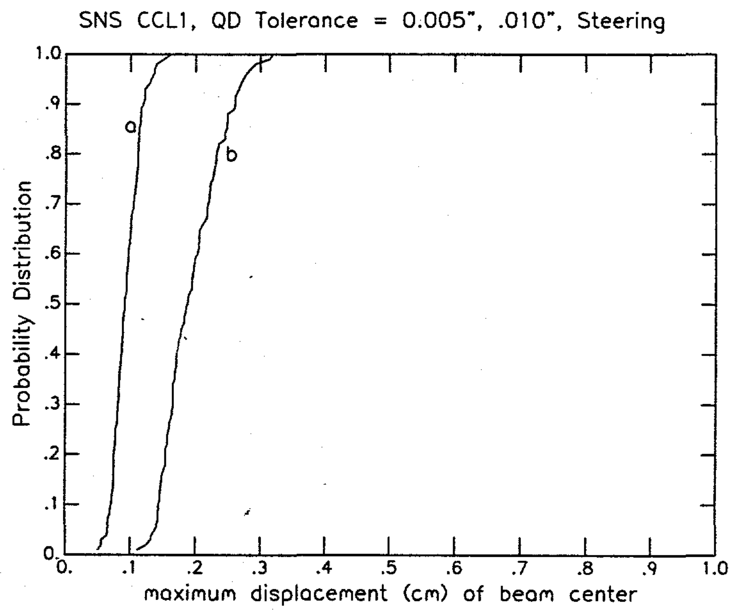


Fig. 10. Probability distribution of the maximum displacement of the beam center in the CCL1 when the tolerance on the random displacements of the quads was 0.005" (a) and 0.010" (b) and the beam is steered at every 5.5 focusing periods (11 quads).

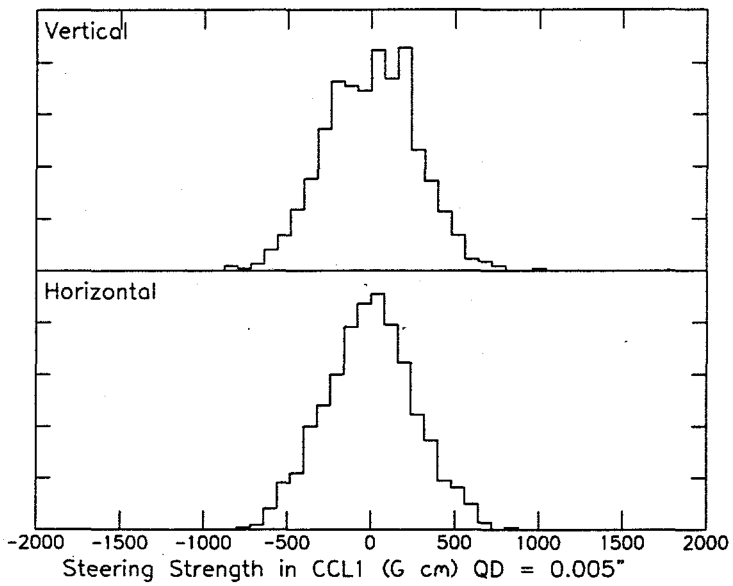


Fig. 11. Histograms of steering strengths used in the 100 runs for the 0.005" error tolerances.

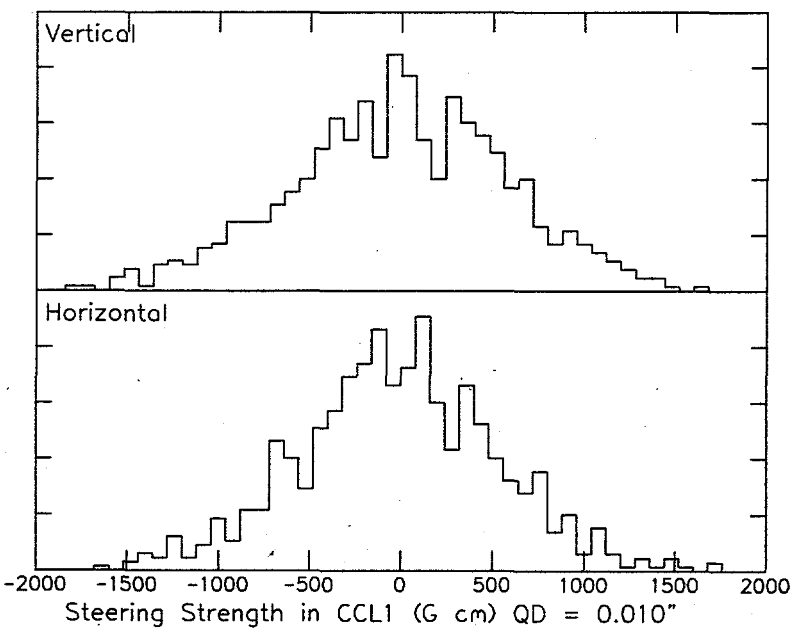


Fig. 12. Histograms of steering strengths used in the 100 runs for the 0.010" error tolerances.

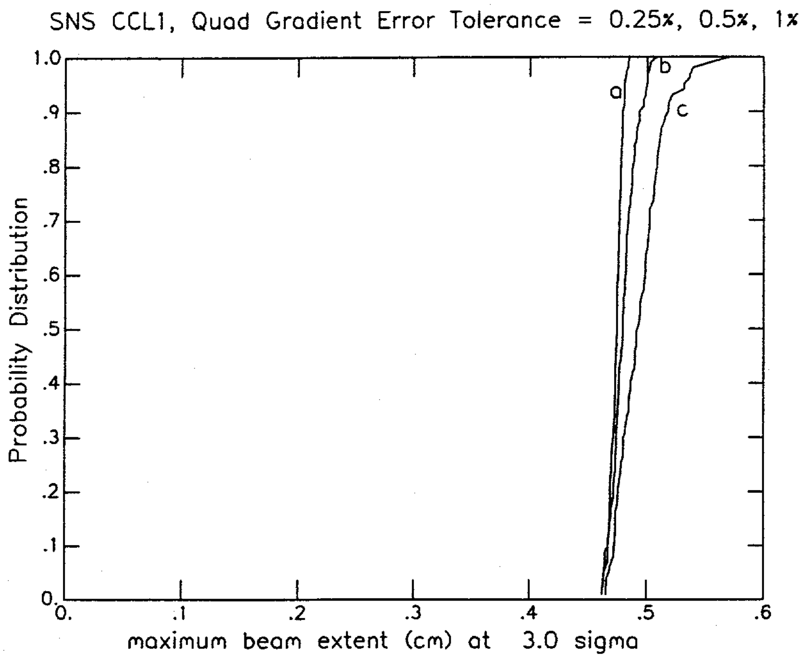


Fig. 13. Probability distributions of the maximum beam extent produced by quad gradient error tolerances of 0.25% (a); 0.5% (b); and 1% (c).

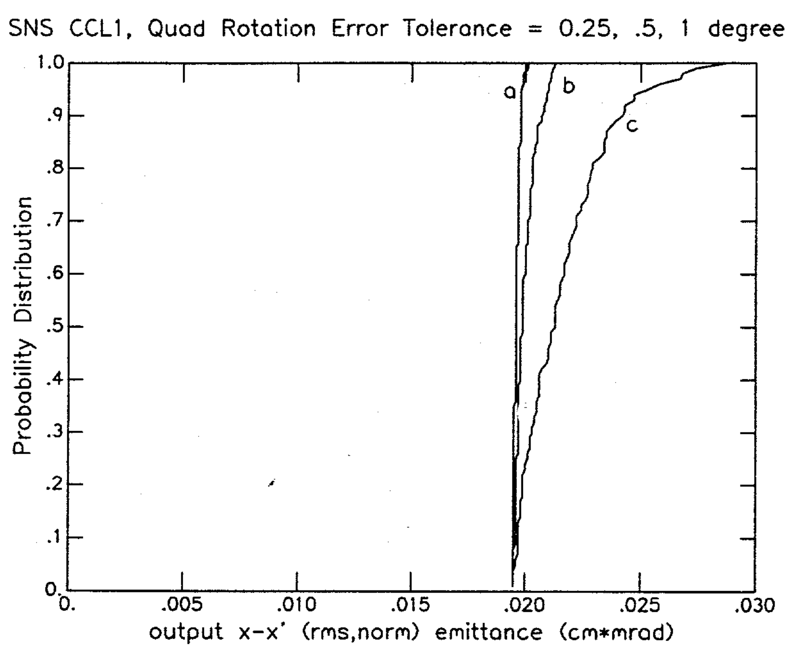


Fig. 14. Probability distributions of the output *effective* emittance in the x-x' phase plane caused by quad rotation error tolerances of 0.25 (a); 0.5 (b); and 1 degree (c).

CCL2: 165.7 - 1000 MeV

Quad displacements

The effects of a quad displacement tolerance of 0.005" is shown in Fig. 15 by the probability distribution curve (a) of the maximum displacement of the beam center in the CCL2. Curve (b) shows the effect of steering every 7.5 focusing periods (15 quads). There are 222 quads in this section of the linac, so there are 15 steering sets. Steering is done at the beginning of the section to get the beam emerging from the CCL1 back on axis. Histograms of the steering strengths are shown in Fig. 16.

Quadrupole gradient errors

probability distributions of the maximum radius of the beam are shown in Fig. 17 for gradient-error tolerances of 0.25%, 0.5% and 1%.

Quad rotation errors

The effects of 0.25, 0.5 and 1 degree tolerances on quad rotation (about its longitudinal axis) are shown in Fig. 18.

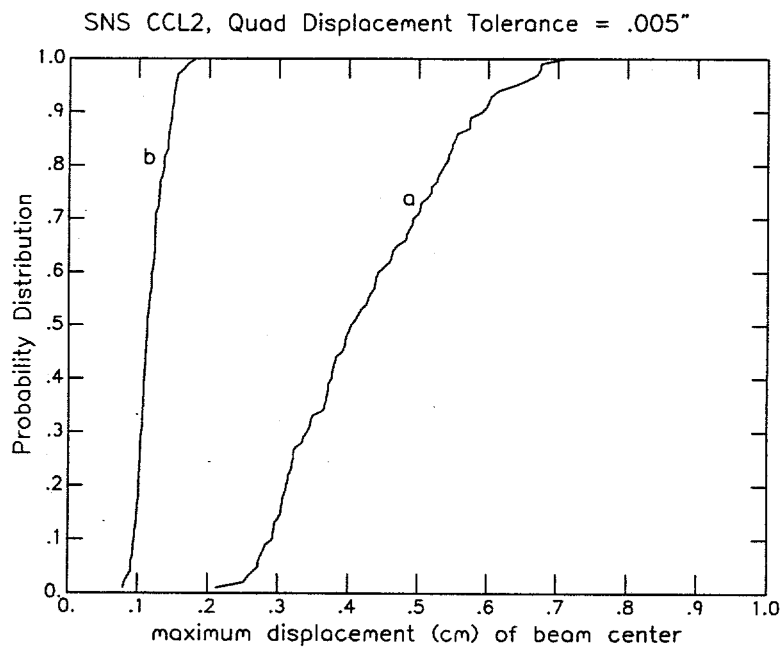


Fig. 15. Probability distribution of the maximum displacement of the beam center in the CCL2 when the tolerance on the random displacements of the quads was 0.005". Curve (a) is with no steering corrections; curve (b) has steering corrections every 7.5 focusing periods (15 quads).

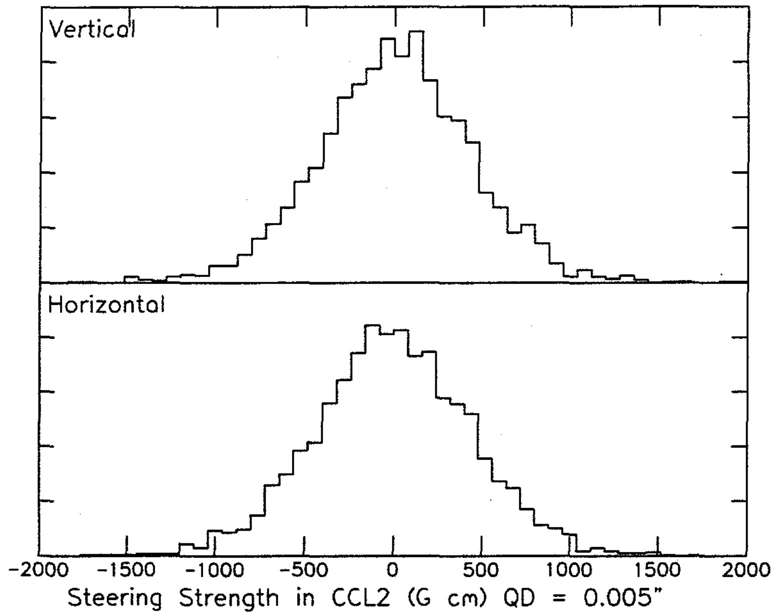


Fig. 16. Histograms of steering strengths used in the 100 runs for the 0.005" error tolerances

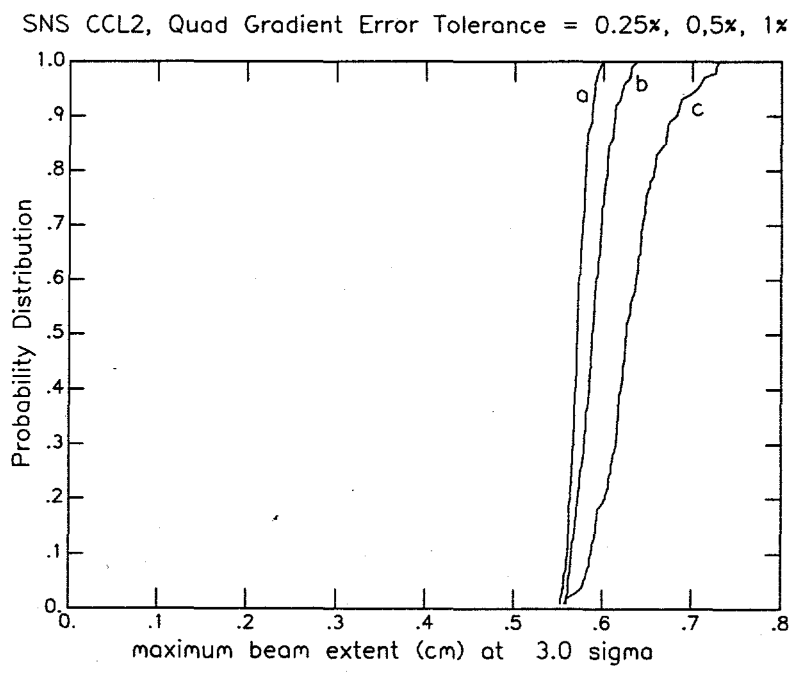


Fig. 17. Probability distributions of the maximum beam extent produced by quad gradient error tolerances of 0.25% (a); 0.5% (b); and 1% (c).

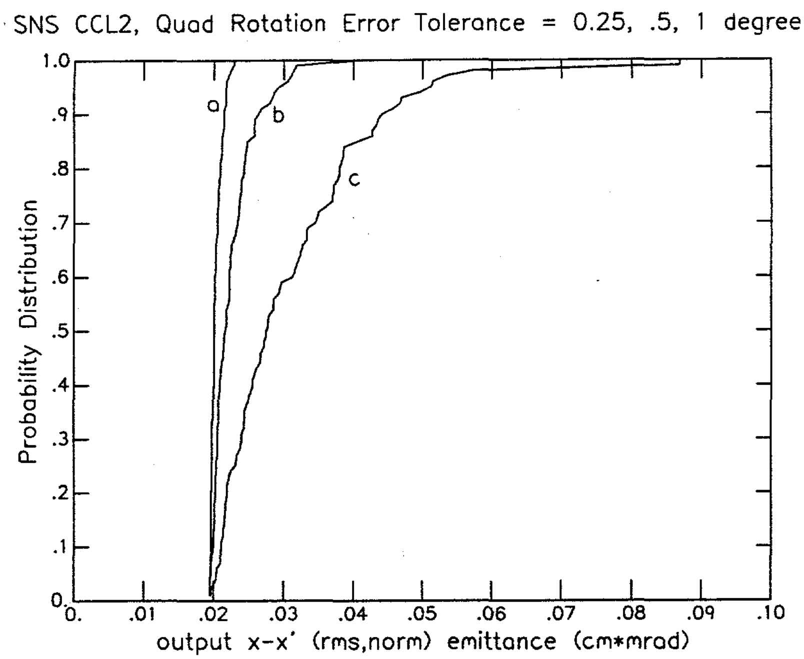


Fig. 18. Probability distributions of the output *effective* emittance in the x-x' phase plane caused by quad rotation error tolerances of 0.25 (a); 0.5 (b); and 1 degree (c).

Entire linac: 2.5 - 1000 MeV

The final step is to put in all the errors at the same time and run the beam though the entire linac, with steering. In the DTL, the following error tolerances were used: quad displacement, 0.004"; quad gradient errors, 0.25%; quad rotation, 0.25 degrees. No steering was done in the DTL. In the rest of the linac, the tolerance on the quad displacements was 0.005" and steering was done. The quad gradient and rotation errors were the same as in the DTL, 0.25% and 0.25 degrees, respectively.

The results, shown in Fig. 19, are presented as probability distribution curves of the filling factor (assuming the beam width is 3 rms widths) in each section of the linac. The labels (a), (b), (c) and (d) denote the results in the DTL, CCDTL, CCL1 and CCL2, respectively. The "bottleneck" occurs in the CCDTL, but this is caused by the fact that the incoming beam from the DTL has not been steered back on axis. More than 75% of the maxima occurred in the first few cavities of the CCDTL, before the first beam steering. After the first steering, the maximum value of the filling factor was 0.636. The filling factor in CCL1 and CCL2 are smaller because the bore radius increases in these structures.

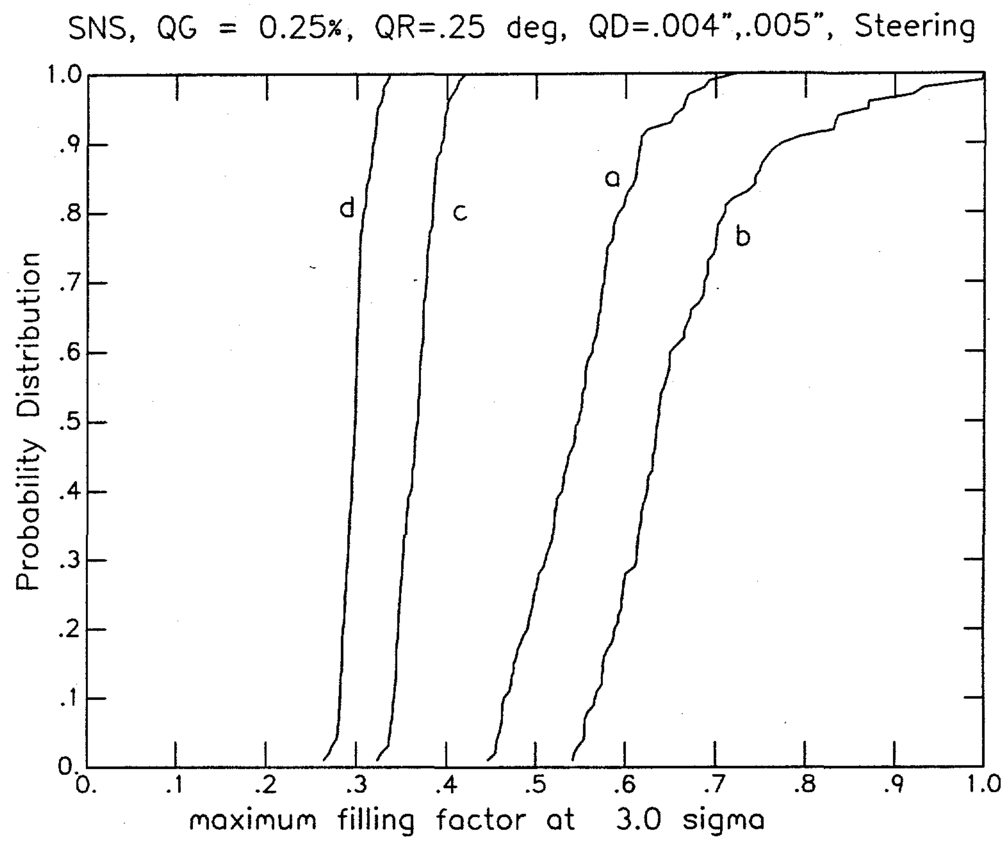


Fig. 19. Probability distribution curves of the filling factor (at 3 rms widths) of the beam in each of the four sections of the linac: DTL (a); CCDTL (b); CCL1, (c); CCL2 (d). Error tolerances throughout were 0.25% for quad gradient errors and 0.25 degrees for quad rotations. The tolerance on quad displacements was 0.004" in the DTL and 0.005" in the rest of the linac. Steering was done in CCDTL, CCL1 and CCL2; none was done in the DTL.