ERROR STUDIES USING PARTRACE, A NEW PROGRAM THAT COMBINES PARMILA AND TRACE 3-D*

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ABSTRACT

PARTRACE is a new program that combines the input format and linac generation of PARMILA with the beam dynamics of TRACE 3-D. The result is an extremely fast-running version of PARMILA that can be used for error studies or for optimizing linacs and transport lines.

The effects of errors, such as quadrupole misalignments, can be studied by making many runs with random errors. The magnitudes of the undesirable consequences, such as beam displacement and emittance growth, can be summarized by probability distributions. These results can be used for setting error tolerances or in estimating the amount of corrective action required.

ERROR STUDIES

The study of the effects of various linac or transport system errors on the particle beam is an exercise in probabilities. For some types of errors, formulae have been derived that relate the magnitude of the effect to the error tolerance. These formulae are useful in that they give a functional relationship between the effect and the parameters of the transport system.

For example, a sequence of randomly misaligned quadrupoles will cause the beam center to oscillate about the axis. One can derive a formula for the rms value of the oscillation amplitude in terms of the quad focal length, quad spacing, the number of quads and the rms value of the quad displacements. However, the probability that the oscillation amplitude will be no larger than the rms value is not immediately obvious. Computer simulations have shown this probability to be between 60 and 65%, and have shown about a 90% probability that the amplitude will be less than 1.5 times the rms value.

The effects of some other types of errors are not so easy to calculate, especially when space-charge forces are significant. In these cases, and when one wishes to consider the effects of many types of errors simultaneously, computer simulations are necessary. Many runs are made through the linac or transport system and tolerances are specified for the various errors to be considered. At each element for which an error tolerance has been assigned, random values within the tolerance limits are chosen for the errors. The undesirable effect has a maximum value at some point along the system for each run. By making many runs to generate probability distributions for these maximum values, one can estimate the probabilities that the undesirable effects will exceed critical limits. These so-called Monte Carlo calculations can take a lot of computer time if multi-particle programs are used. One such program is PARMILA,[1] a widely used program for the design and simulation of drift-tube linacs (DTLs). By replacing the multi-particle calculations in PARMILA with the beam-ellipsoid calculations of TRACE 3-D,[2] the computer time can be considerably reduced.

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PARTRACE

A new program, PARTRACE, combines the input format and linac generation of PARMILA with the beam dynamics of TRACE 3-D. It calculates the dynamics of the beam center and of the beam ellipsoid, including space-charge forces and emittance growth in rf gaps.

The input for PARTRACE is a slightly modified PARMILA input file. The modifications occur on the INPUT, OPTCON and BEGIN cards. The initial beam is specified on the INPUT card by Twiss parameters and emittances, either total unnormalized or rms normalized. The OPTCON card specifies the output format and, for error studies, the extent of the beam in multiples of the rms width. The number of runs to make when doing error studies is specified on the BEGIN card.

The output from PARTRACE is a formatted output file. One format option is the Twiss parameters and rms emittances at the locations specified on the OUTPUT cards. A second option outputs the coordinates of the beam center, the beam widths in x, y and z, and the rms emittances. A third option is the probability distributions computed in the error studies.

When doing error studies, PARTRACE examines the following quantities at the locations specified on the OUTPUT cards (usually at every cell): the transverse coordinates (x, x′, y, y′) of the beam center; the maximum extent of the beam (RMAX) from the axis; the quantity FMAX=RMAX/RD, where RD is the drift-tube bore radius; and the normalized rms emittances in x, y, and z. (FMAX is a measure of how close the edge of the beam comes to the drift tube. FMAX=1 means that the beam is just scraping the bore.) The maximum values of each of these quantities are saved as the beam passes through the DTL and are stored in arrays at the end of each run. After N runs, these arrays are sorted to obtain probability distributions which are then written to the output file. An example of this output option is shown in Table 1.

The types of errors considered by PARTRACE are: quadrupole displacements; quadrupole tilt (pitch and yaw); quad rotation (roll); quad gradient errors; tank displacement; tank tilt; rf amplitude and phase errors; and rf amplitude tilt errors.

EXAMPLE

As an example, PARTRACE has been used for studying the error tolerances for a drift-tube linac that accelerates 25 mA of protons from 2 to 11 MeV in a single tank of 38 cells. This linac is similar to one designed by AccSys Technology, Inc. for producing radioisotopes to be used in positron emission tomography.[3] The average axial electric field is 4.025 MV/m, and the 1-inch long quadrupoles have gradients of 16 kG/cm. The drift-tube bore radius is 0.5 cm. In this example, 100 runs were made for each set of error tolerances, and the beam edge was assumed to extend to a distance of three times the rms width.

The probability distribution for FMAX when the error tolerances are 0.003" on the quad displacements and 0.010" on the tank displacement is shown in Fig. 1. The curve shows a probability of about 90% that the beam edge will not exceed 70% of the bore. With no errors, FMAX is 0.505.

Quadrupole rotations about the longitudinal axis cause an x-y coupling that results in an effective emittance growth. That is, the area of the projections on the x-x′ and y-y′ planes increase although the volume in four-dimensional phase space remains constant. Figure 2 shows the probability distribution for the effective emittance when the error tolerance on quad rotations is one degree. The curve shows about a 20% chance that the effective growth will be greater than 25%.

When the quad displacement, tank displacement and quad rotation errors mentioned above are combined with a 2% error tolerance on the quad gradients, the probability distribution for FMAX shown in Fig. 3 is produced. This curve shows a 90% probability that the beam edge will not exceed 75% of the bore, a result not much worse than that produced when only quad and tank displacements were considered.

FUTURE DEVELOPMENT OF PARTRACE

PARTRACE has the potential of being a useful tool for the designers of drift-tube linacs. Because of its speed, PARTRACE could be used for optimization problems such as matching and finding the best input beam characteristics for a DTL. It could be made to operate in an interactive mode, where the user would issue commands through a keyboard and observe results on a graphic display. The extended fields in permanent-magnet quadrupoles could be included, as they are in TRACE 3-D. PARTRACE will undoubtedly evolve to meet the user′s needs.

REFERENCES

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2. K.R. Crandall, "TRACE 3-D Documentation," Los Alamos Report LA-11054-MS, August 1987.
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Table 1. Example of PARTRACE output for error studies.

QD=.003", TD=.010", QR= 1 degree, QG=2%

pdf	xcmax (cm)	ycmax (cm)	xpcmax	ypcmax	rmax (cm)	fmax	exout (norm rms,	eyout pi*cm*mrad)	ezout
0.010	0.0359	0.0248	0.0018	0.0018	0.2771	0.5541	0.0099	0.0099	0.0193
0.020	0.0388	0.0424	0.0019	0.0018	0.2814	0.5628	0.0099	0.0100	0.0194
0.030	0.0408	0.0427	0.0020	0.0019	0.2824	0.5648	0.0099	0.0100	0.0194
0.040	0.0422	0.0435	0.0022	0.0020	0.2853	0.5706	0.0099	0.0100	0.0194
0.050	0.0426	0.0447	0.0022	0.0020	0.2866	0.5732	0.0100	0.0100	0.0194
0.060	0.0428	0.0449	0.0023	0.0021	0.2879	0.5758	0.0100	0.0100	0.0194
0.070	0.0444	0.0456	0.0023	0.0022	0.2955	0.5910	0.0101	0.0100	0.0194
0.080	0.0458	0.0462	0.0023	0.0022	0.2969	0.5937	0.0101	0.0100	0.0194
0.090	0.0491	0.0467	0.0024	0.0022	0.3006	0.6013	0.0101	0.0101	0.0194
0.100	0.0492	0.0472	0.0024	0.0023	0.3070	0.6140	0.0101	0.0101	0.0194
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0.900	0.1311	0.1383	0.0057	0.0056	0.3825	0.7651	0.0136	0.0136	0.0195
0.910	0.1322	0.1386	0.0058	0.0057	0.3855	0.7710	0.0138	0.0137	0.0195
0.920	0.1322	0.1403	0.0059	0.0058	0.3884	0.7768	0.0138	0.0138	0.0195
0.930	0.1377	0.1474	0.0059	0.0059	0.3936	0.7871	0.0143	0.0143	0.0195
0.940	0.1409	0.1510	0.0060	0.0064	0.3963	0.7925	0.0144	0.0144	0.0195
0.950	0.1498	0.1533	0.0061	0.0066	0.4013	0.8027	0.0145	0.0145	0.0195
0.960	0.1533	0.1562	0.0063	0.0066	0.4035	0.8070	0.0145	0.0145	0.0195
0.970	0.1534	0.1564	0.0063	0.0067	0.4036	0.8072	0.0153	0.0153	0.0195
0.980	0.1571	0.1598	0.0070	0.0068	0.4051	0.8102	0.0155	0.0155	0.0195
0.990	0.1581	0.1725	0.0076	0.0077	0.4069	0.8138	0.0175	0.0176	0.0195
1.000	0.1603	0.1928	0.0086	0.0085	0.4123	0.8246	0.0202	0.0203	0.0195

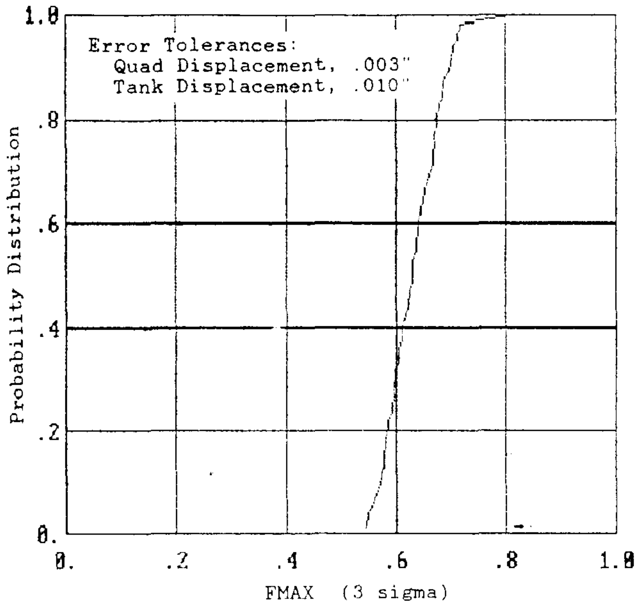

Fig. 1. Probability distribution for FMAX generated by PARTRACE from 100 runs having error tolerances of 0.003" for quad displacements and 0.010" for tank displacements in the example DTL discussed in the text.

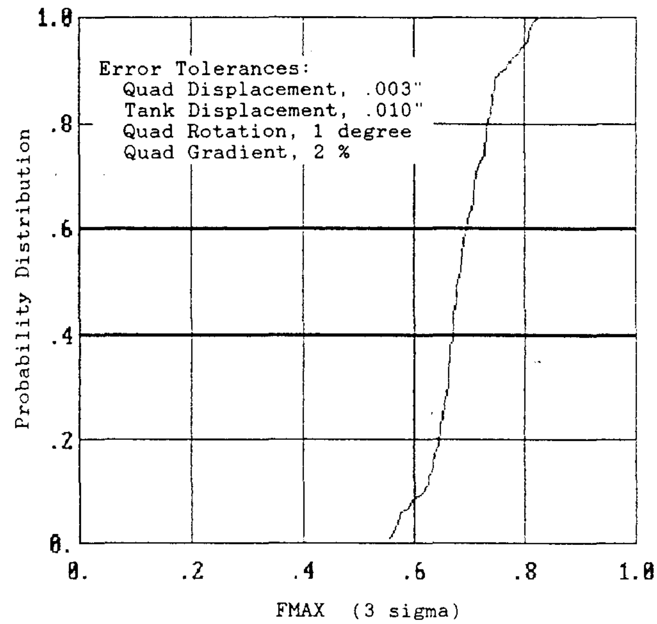

Fig. 3. Probability distribution for FMAX generated by PARTRACE from 100 runs through the example DTL when error tolerances were specified for quad displacements, tank displacement, quad rotations and quad gradients.

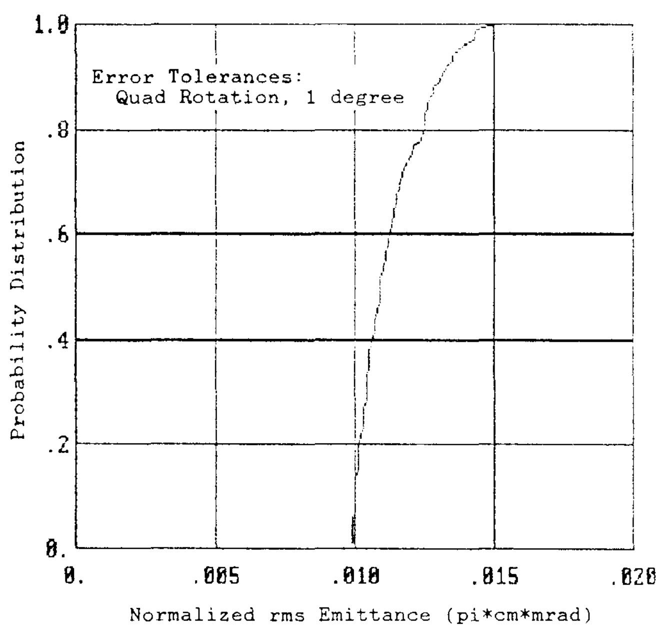

Fig. 2. Probability distribution for the effective transverse emittance calculated by PARTRACE from 100 runs through the example DTL when the error tolerance on quad rotations was 1°.