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[*]Error Analysis of a 20MeV DTL for PEFP

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Abstract

In this work, we present the first result of error analysis in a 20MeV drift tube linac (DTL) for the proton engineering frontier project (PEFP). From the calculation of beam dynamics under varying the DTL error condition, we get the error sensitivity of each variable and their tolerance limit. We use the transverse and longitudinal emittances and maximum beam size as indicators in order to estimate the error effect.

1. Introduction

One of main goal of the PEFP project is the construction of proton linac to accelerate the 20mA proton beam up to 100MeV in the following 10 years. The first stage will be completed in 2005 and we will get 20 MeV proton beam. In this low energy part, the main accelerating structure is composed of proton source, radio frequency quadrupole (RFQ) to get 3MeV proton beam, and drift tube linac (DTL). A main work in this period is to design and construct the DTL for 20MeV proton beam.

The first step to design the drift tube linac is the process to acquire information of the typical cells used for various energy of proton beam. Then we have to select the geometric parameters of DTL tanks such as cell length, gap length, etc. In parallel with the process, we should test whether this structure is satisfied with the constraints from the beam dynamics point of view. We have used Poisson/Superfish and PARMILA codes to attain these purposes [1,2].

Since it's impossible to construct the machine without error, one important next step is

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determination of the tolerance limit for each parameter. There are a lot of error sources in the accelerating structure and accelerated beam properties. They can be divided into three groups[3]. The first is beam related error which includes displacement of beam from the center of axis for acceleration, beam mismatch in the transverse and longitudinal phase space, the shift of initial energy from the planned value, etc. The second group is time independent error which is mainly related to the fixed accelerating components. One is structure error which includes the tank length, gap and cell length, higher order component in focusing quadrupole magnet field, quadrupole gradient times length, etc. Another is tuning error such as RF field amplitude and phase, field flatness, etc. The other is alignment error such as displacement of tanks and quadrupole magnets, quadrupole field tilt, pitch error (rotation about x axis), yaw error (rotation about y axis) and roll error (rotation about z axis), etc. The third group of errors is called time dependent error which includes amplitude and phase errors of the RF source and its feedback process, mechanical vibration of the structure such as drift tube supported by stem, etc.

The main goal of this work is to quantitatively analyze the error effect and give the acceptable level of tolerance limit to each parameter. The parameter set we choose for the simulation includes the initial energy, transverse emittance, RF connected with its magnitude, phase, and tilt, and finally focusing quadrupole magnet related to its magnitude, shift of center, and rotations about x, y, and z axes.

The contents of this report are as follows. Section 2 contains a brief summary of DTL design parameters to be used in beam dynamics simulation. The main result of the error analysis is included in section 3. The final conclusion is presented in section 4.

2. Brief Summary of DTL Parameters

Our DTL is designed to accelerate proton beam of 20 mA from 3 MeV to 20 MeV via 4 tanks. The maximum input power is 900kW and RF frequency is 350 MHz. The schematic plot of a typical DTL tank is given in figure 1. Table 1 shows the final design values of the geometrical parameters for the DTL cavities. They are used to generate DTL cell information by Poisson/Superfish code[1] as well as to calculate beam dynamics by Parmila[2]. The meaning of each parameter can be found in Ref. 2.

Further information for each tank is presented in Table 2 which includes the cell number, accelerating field strength, transverse focusing structure, and synchronous phase. We select FFDD lattice structure for transverse focusing of the beam. The cell numbers in each tank or tank length is determined by the condition that each tank consumes the same amount of RF power. The result of beam dynamics calculation by using this parameter set can be found in Ref. 4.

For the simulation of beam dynamics, we have used the matched beam for the given DTL structure whose normalized RMS emittances are 0.023 cm-mrad in transverse directions and 0.037 cm-mrad in longitudinal direction, respectively. We also use the 6-D waterbag model for the particle distribution in the phase space. In this model, particles are randomly distributed into a 6-dimensional ellipse in the phase space.

3. Error Analysis

In this work, we use PARMILA code to analyze the error effects on the beam dynamics and get the tolerance limit acceptable for each variable. The first item of error analysis is the input energy. The second is transverse emittance of input beam. The third set is quadrupole error in connection with its magnitude, displacement of its center in transverse direction, rotation about x, y, and z axes which are called pitch, yaw, and roll errors, respectively. The RF error is the final set which includes errors coming from its amplitude, phase, and RF field tilt.

To get the result, we use the 100,000 particles for each simulation and get the average value and the standard deviation from the 10 data set for each error case. The quoted error values in the following figures are the maximum values and the code is designed to randomly select one error value below the limit. After scanning the output values of emittance or beam size, we can select their maximum values for each case which become a data set for the resulting figures.

Figure 2-1 shows the result of beam dynamics under the condition that the center of energy in the particle distribution is shifted between 2.96 MeV and 3.05 MeV. The upper left and right plots are related to the growth of emittances in transverse and longitudinal directions, respectively. The maximum beam size and RMS size in transverse direction are shown in lower left and right parts in the figure. The real line is the result for the x-direction and dashed line for y-direction. The figure 2-2 is plot for the standard deviation for the simulation result. We find that the input energy is a sensitive variable to maintain beam stability. For example, if the energy is 2.95 MeV, simulation shows beam loss, average 3 particles in our case.

The remaining figures follow the same presentation order as the figure 2-1 and 2-2.

The error effect under varying transverse emittance is given in figure 3-1 and 3-2. In these plots, the x-axis represents the emittance increase in percentage from that of matched beam. The transverse emittance and beam size increase almost linearly with the mismatch of initial emittance.

The errors related with quadrupole magnet contain the variation of the field gradient times length (figure 4-1 and 4-2), the displacement of field center in transverse direction (figure 5-1 and 5-2), and the rotation about the x, y, and z-axes (figure 6-1 and 6-2). Figure 4-1 shows that the magnitude of focusing magnet is a less sensitive variable of error with respect to beam dynamics. In figure 5-1 and 5-2, the black line represents the shift of center of quadrupole magnet in x-direction and red line in y-direction. We find that the displacement of magnet center up to several tens micrometer don’t give serious impact on the beam dynamics. The black, red, and green lines in figure 6-1 and 6-2 represent pitch error, yaw error, and roll error, respectively. For the case of transverse emittance given in the upper left part of figure 6-1, the most sensitive error source is the rotation about z-axis or roll error. The maximum beam size begins to grow even for small rotations about x and y-directions. However it remains almost constant until the roll error becomes about 3 degrees. We also note that the standard deviation of the data for rotation error of the magnet becomes relatively large to be about 15 % for the maximum beam size under the roll error.

Figure 7-1 and 7-2 show the effect on beam dynamics of RF amplitude error (black line) and phase error (red line). We note that these give the similar behavior as that obtained in the case of the displacement of quarupole magnet center (figure 5-1 and 5-2). The result of RF tilt, which is the inclination of RF field in the tank, is given in figure 8-1 and 8-2.

We also give the combining error effects in figure 9-1 and 9-2. The red, green, and black lines represent the RF error, quadrupole error, and RF plus quadrupole errors. The scales for the horizontal axis are degree, percentage, and micrometer divided by 10 according to each variable. The figures explicitly show that the quadrupole error is more serious than the RF errors in the beam dynamics point of view.

The table 3 gives the tolerance limit for our DTL parameters determined by the simulation results. They seems much tighter than the values suggested in the figures because we should include the unknown effects coming from other errors which is not considered here.

4. Conclusion

The main purpose of this work is the error analysis of 20MeV DTL for PEFP to get some idea which variable gives serious impact on the beam dynamics and give the tolerance limit on the parameters.

We include the errors coming from the initial energy, transverse emittance of input beam, focusing quadrupole magnet, and RF. The quadrupole error contains magnitude error, displacement error of magnet center, and rotation errors about x, y, z-axes. RF error covers amplitde and phase errors and RF tilt errors. We can show that the initial energy and parameters related with quadrupole magnet are important variables to control in order to maintain the beam quality as we hope it would. Especially, the roll error related with rotation about z-axis is very sensitive variable which gives very large increase of transverse emittance as well as maximum beam size.

The results are summarized in the table 3 that shows tolerance limits on the related variables. The values are selected by taking the enough margin for unknown effects into consideration.

5. References

1. Poisson/Superfish version 6.25; documentation, LA-UR-96-1834.
2. PARMILA version 1.12; documentation, LA-UR-98-4478.
3. D. Raparia, et al, Error and Tolerance studies for the SSC Linac, PAC'93 Conf. Proc., 3585-3587 (1992).
4. Y.S. Cho, et al, KOMAC DTL (3 ~ 20 MeV) preliminary design report, PE-30000-DD-P001 (2002).

Table 1 DTL design parameters

Parameter	Symbol	Value
RF frequency		350 MHz
RF power		900 kW
Reference temperature		40 °C
Initial energy		3 MeV
Final energy		20 MeV
Tank diameter	D	54.4408 cm
Drift-tube diameter	d	13 cm
Bore radius	R_b	0.7 cm
Drift-tube face angle	α_f	10 degrees
Drift-tube flat length	F	0.3 cm
Corner radius	R_c	0.5 cm
Inner nose radius	R_i	0.2 cm
Outer nose radius	R_o	0.2 cm
Stem diameter	d_{stem}	2.6 cm
Frequency tolerance	δf	0.001 MHz

Table 2 The DTL parameters for each tanks

	Tank 1	Tank 2	Tank 3	Tank 4
Number of cells	51	39	33	29
Energy range (MeV)	3.0 ~ 7.18	7.18 ~ 11.50	11.50 ~ 15.80	15.80 ~ 20.0
Tank length (cm)	444.064	464.876	475.525	477.580
Number of Quads	52	40	34	30
Focusing lattice	FOFODODO	FOFODODO	FOFODODO	FOFODODO
Φ_s (degree)	-30.0	-30.0	-30.0	-30.0
Total power (kW)	225	225	224	221
Effective Quad length (cm)	3.5	3.5	3.5	3.5
Quad gradient (kG/cm)	5.0	5.0	5.0	5.0
E_0 (MV/m)	1.302	1.302	1.302	1.302
Transit time factor	0.84 ~ 0.83	0.83 ~ 0.81	0.81 ~ 0.79	0.79 ~ 0.77

Table 3 Tolerance limit of DTL parameters

Variables	Tolerance limit
Quadrupole gradient times length	1 %
Displacement of magnet center	10 μm
Pitch, yaw, and roll errors of the magnet	1°
RF amplitude	1 %
RF phase	1°
RF tilt	1 %

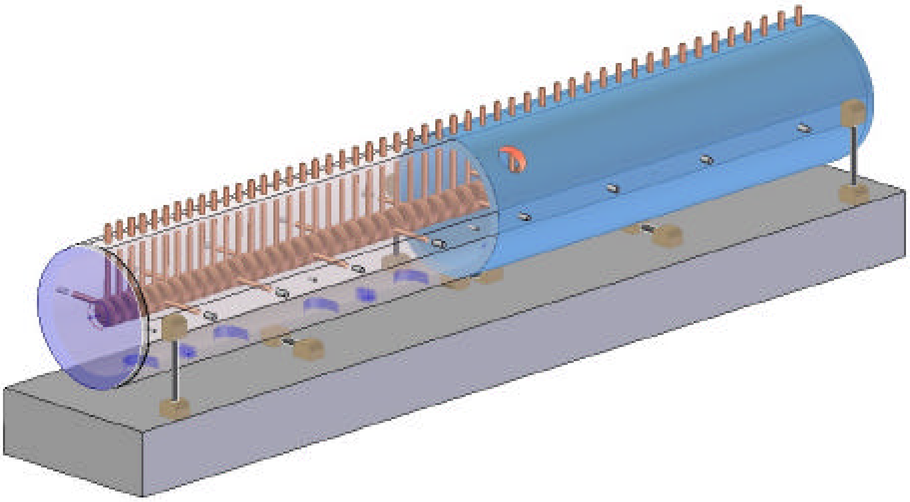

Figure 1 Schematic plot of a DTL tank

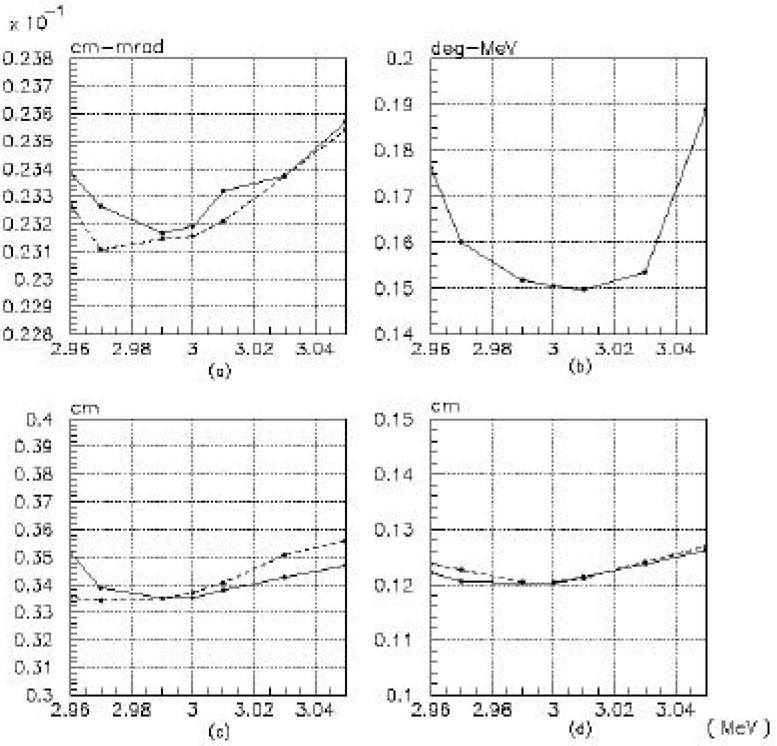

Figure 2-1 Error in center of energy distribution

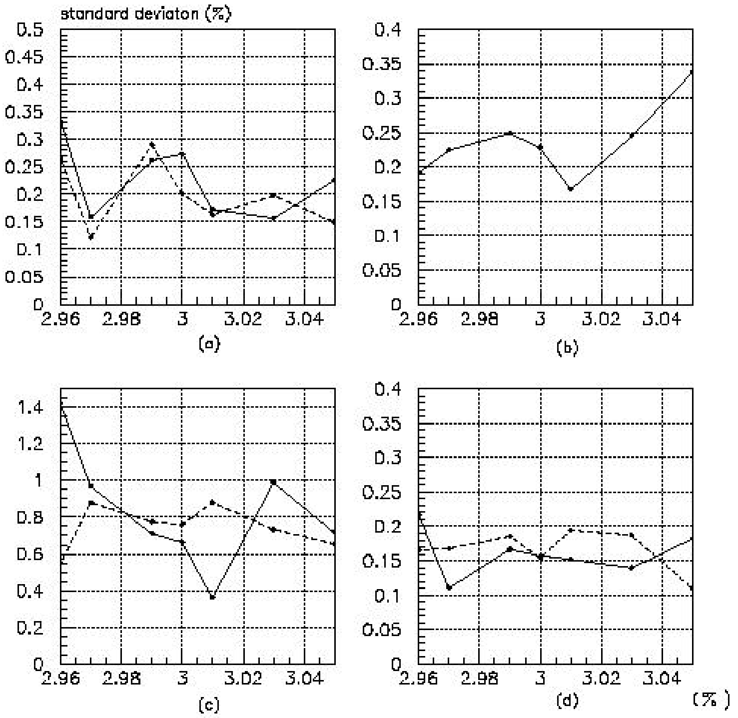

Figure 2-2 Standard deviation for figure 2-1

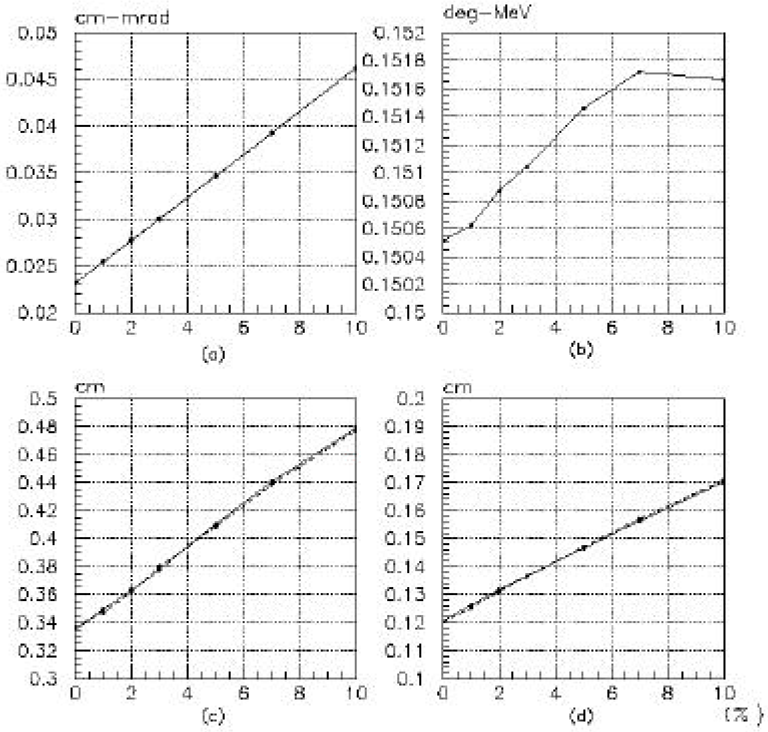

Figure 3-1 Error in transverse emittance

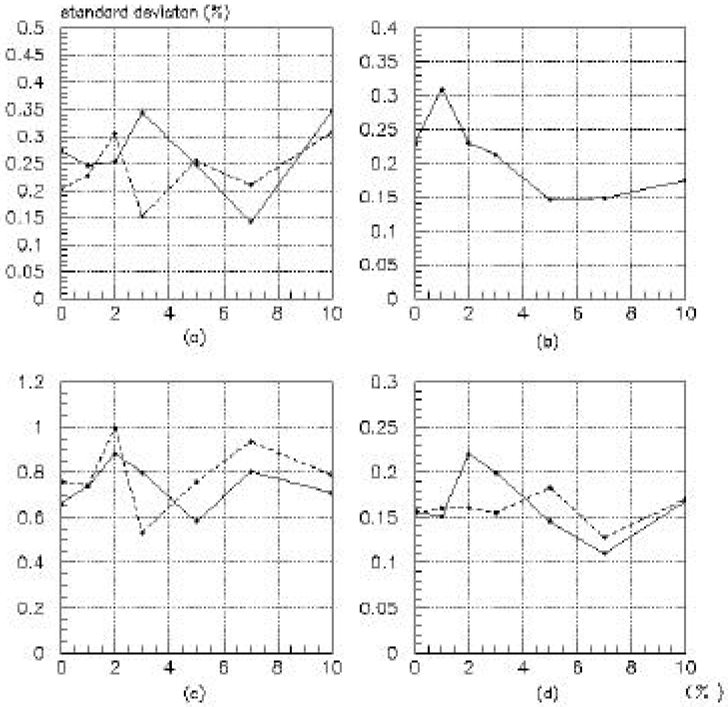

Figure 3-2 Standard deviation for figure 3-1

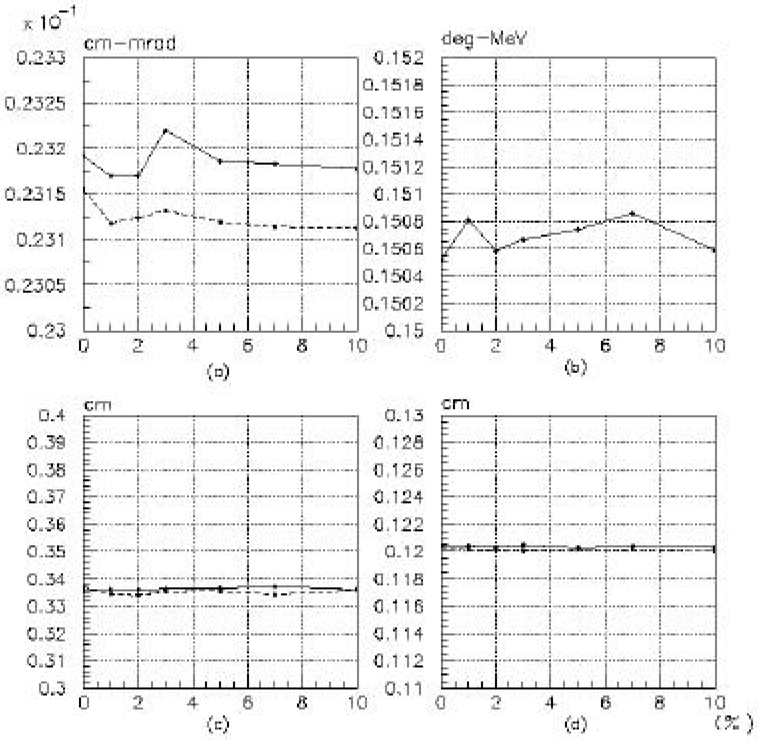

Figure 4-1 Error in magnitude of Quad magnet

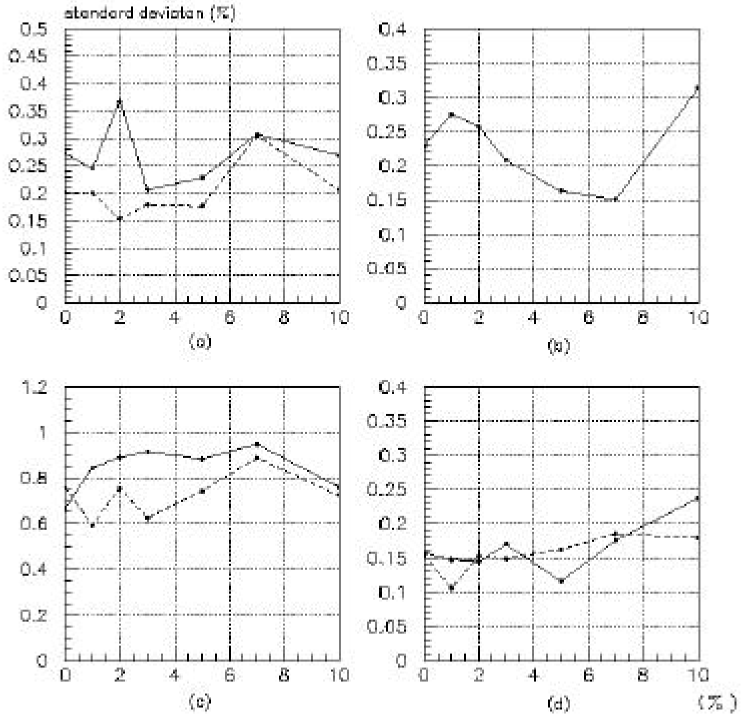

Figure 4-2 Standard deviation for figure 4-1

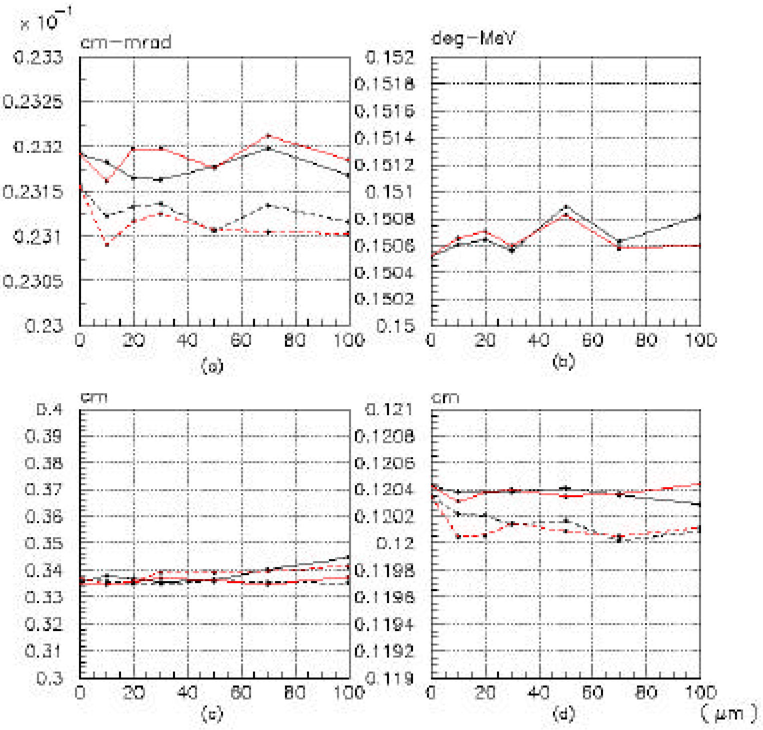

Figure 5-1 Error in center of Quad magnet field in transverse direction

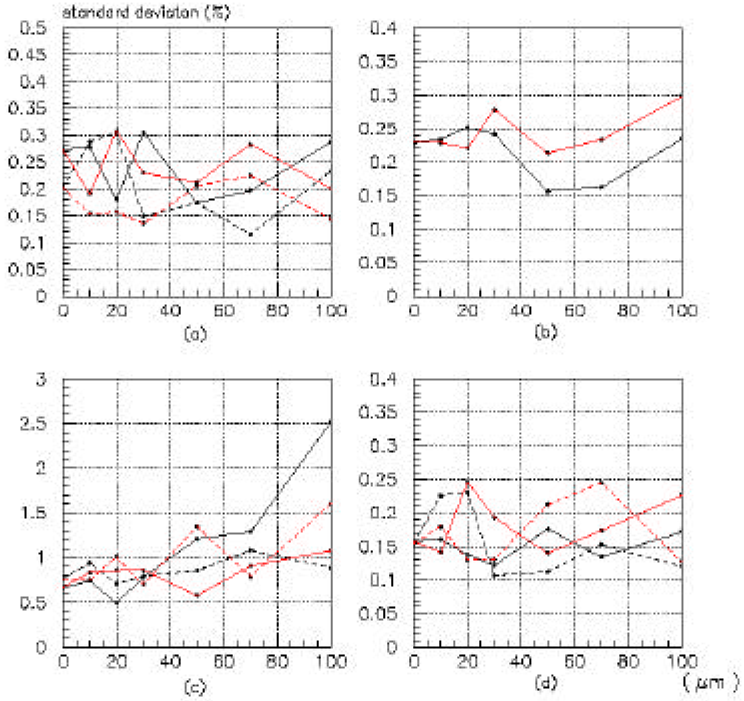

Figure 5-2 Standard deviation for figure 5-1

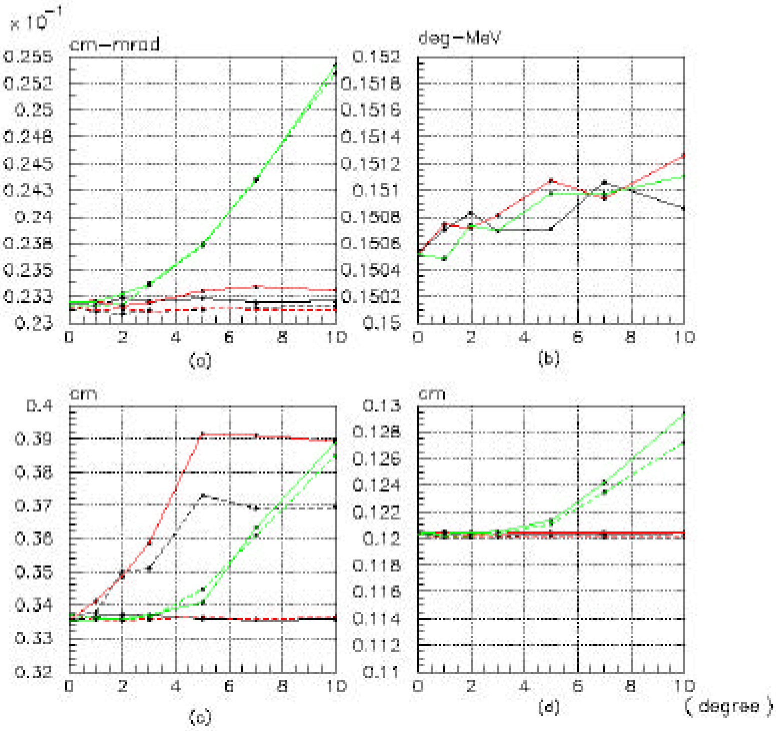

Figure 6-1 Error from rotation of Quad magnet

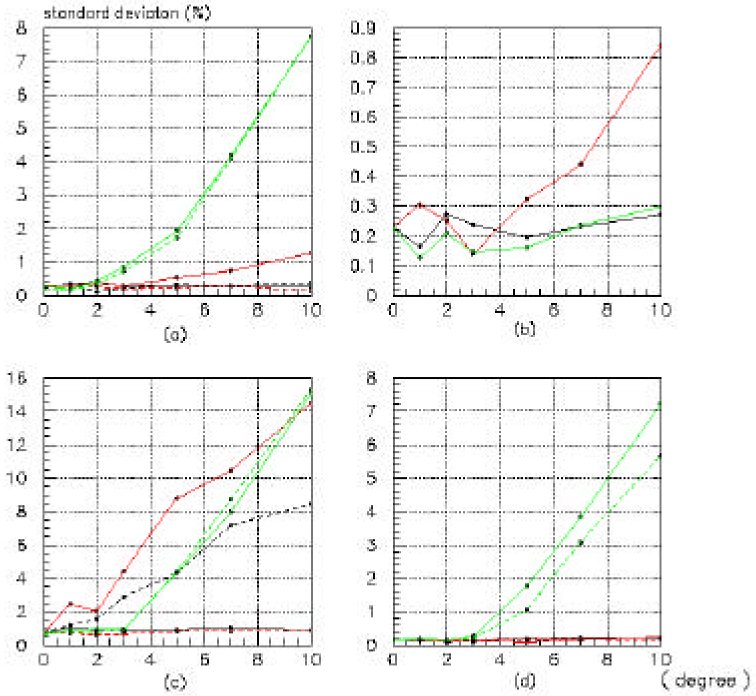

Figure 6-2 Standard deviation for figure 6-1

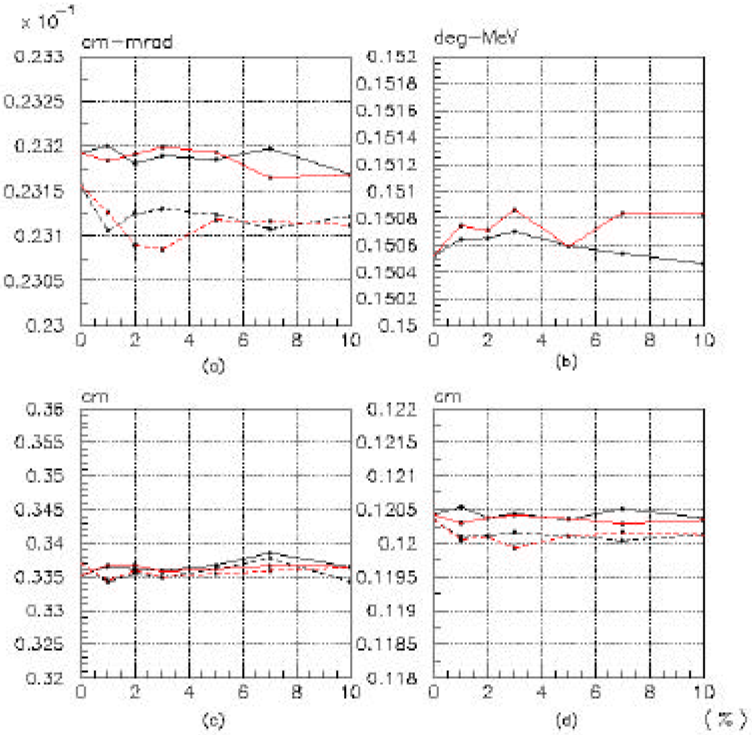

Figure 7-1 Error in RF magnitude and phase

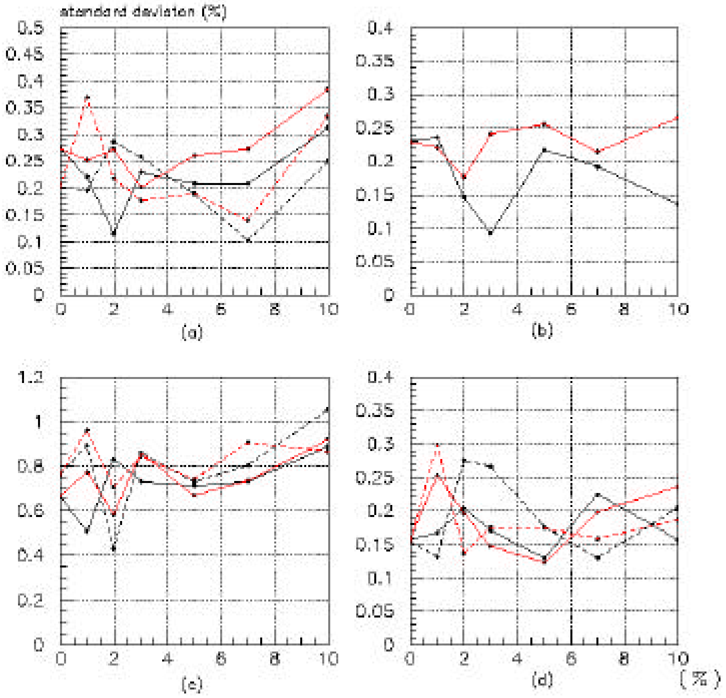

Figure 7-2 Standard deviation for figure 7-1

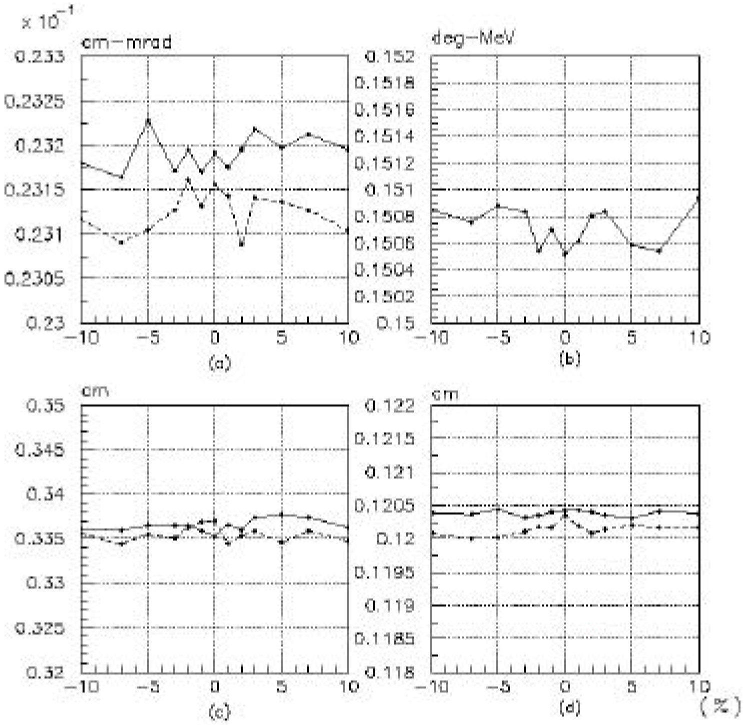

Figure 8-1 Error in RF tilt

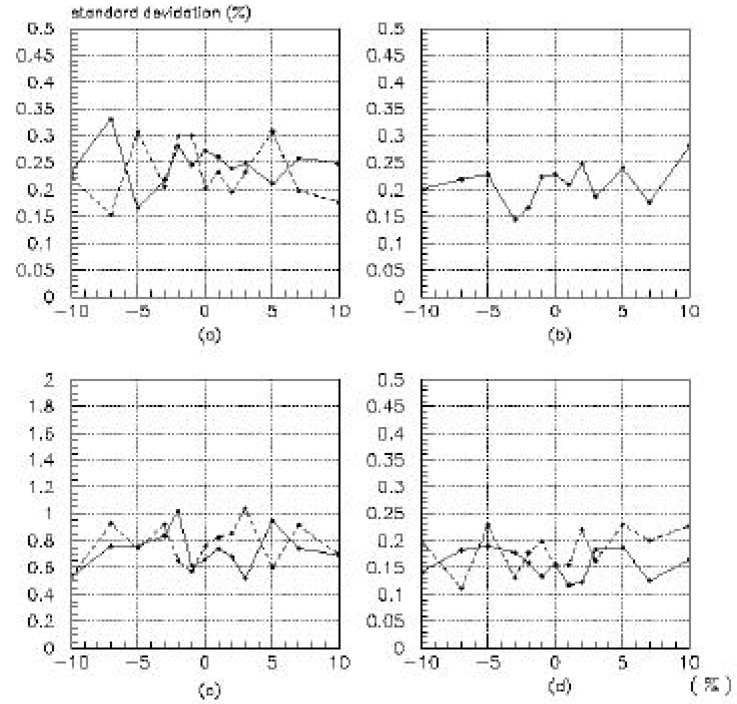

Figure 8-2 Standard deviation for figure 8-1

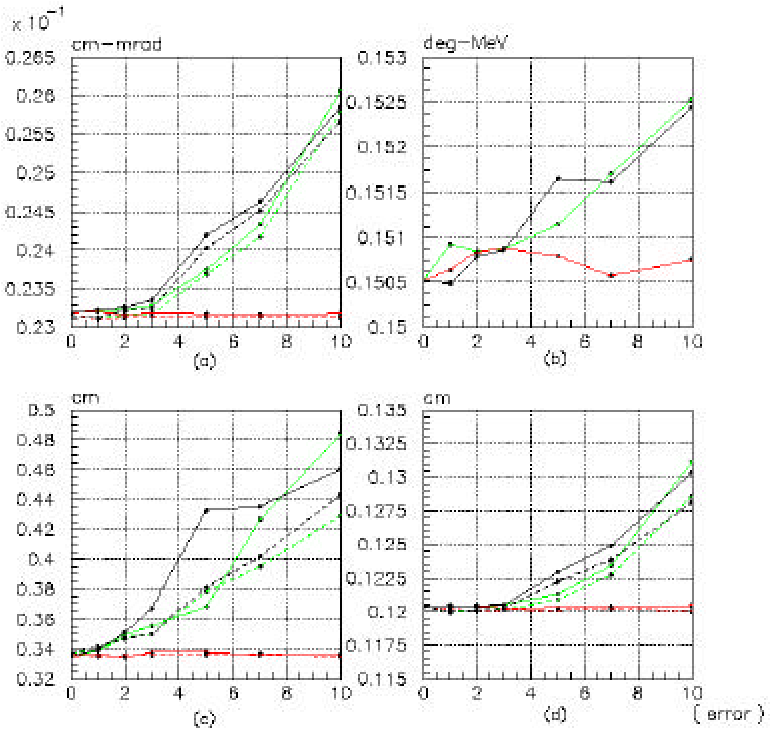

Figure 9-1 Error in RF, Quad, and RF + Quad

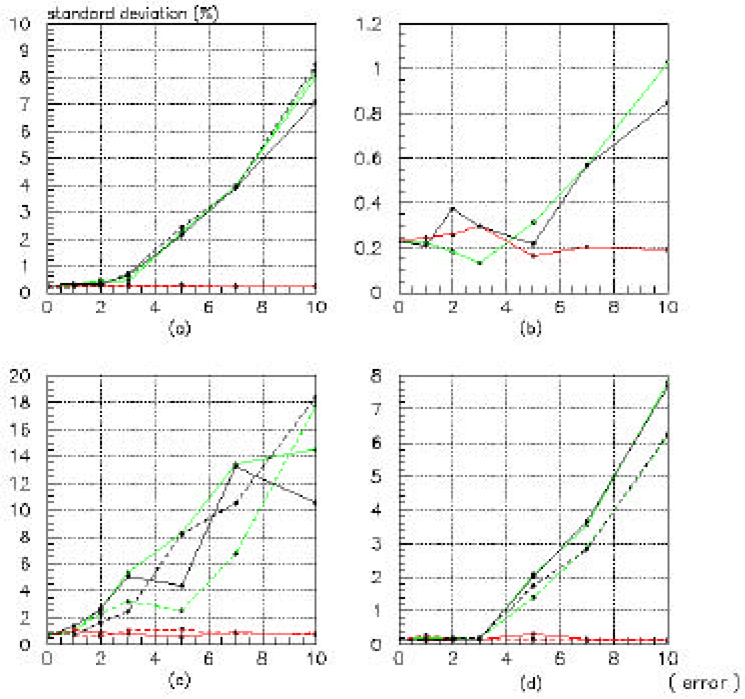

Figure 9-2 Standard deviation for figure 9-1