Beam Dynamics Study Of PIP-II Superconducting Linac in the Presence of Misalignment Errors

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Introduction

- The misalignment errors in the beam line components may lead to emittance dilution and beam loss in worst condition.
- In the present analysis, misalignment error was applied on the cavities and magnets and their effect was studied on the final beam properties.
- Error study was carried out for the superconducting part of the PIP-II linac starting from HWR section.

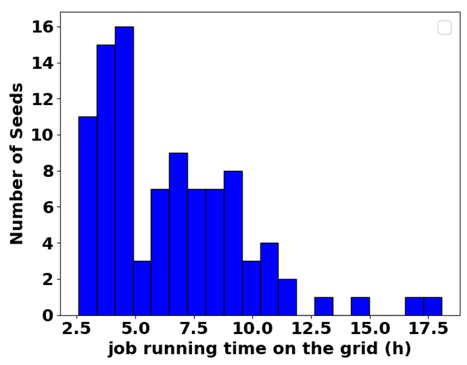
Set Up

- **Displacement -** shift in the element position along vertical, horizontal or longitudinal directions.
- **Tilt and roll -** rotation of the element from centre about vertical/horizontal and longitudinal axis, respectively.
- A set of random displacement and tilt errors were applied with Gaussian distribution in beam dynamics code TraceWin.
- To execute the large number of simulations in parallel, computing grid at Fermilab was used.

Relative Emittance Dilution

$$\frac{\Delta\epsilon_i}{\epsilon_i} = \frac{\left(\epsilon_{i,error} - \epsilon_{i,nominal}\right)}{\epsilon_{i,nominal}} \times 100$$

Large Scale Computing



Time taken by the seeds to complete the simulation successfully on the grid. For a test case, simulations for a set of 100 seeds with 100k initial particles were launched on the grid. Time in this figure includes waiting time in the que and processor runtime.

Nominal Alignment Budget

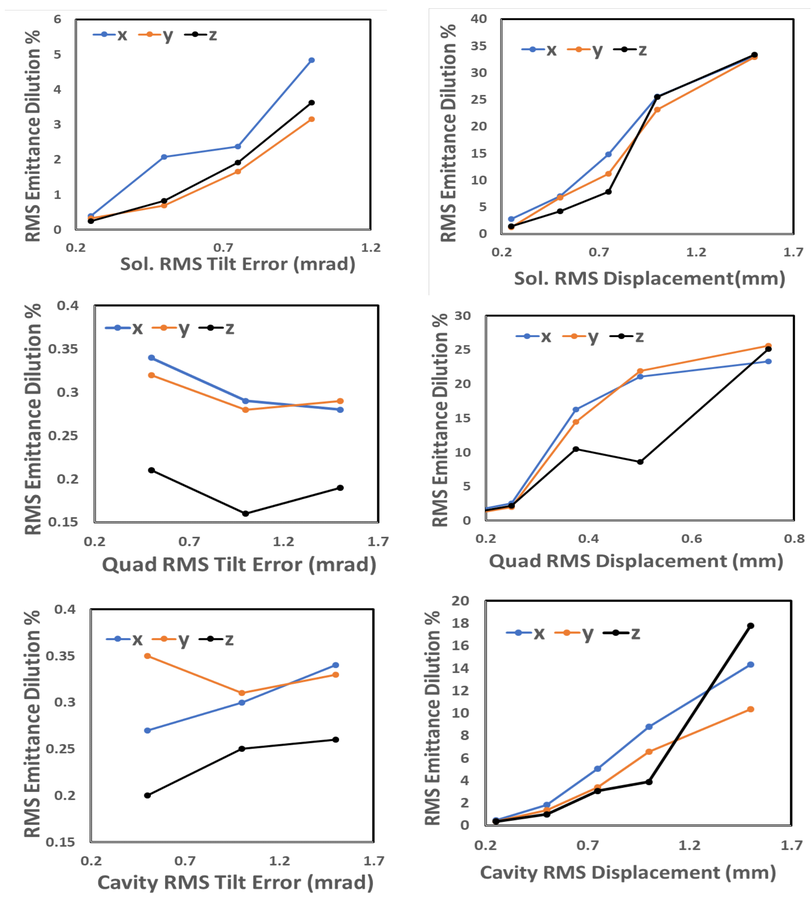
Longitudinal acceptance of the linac. The beam falls well within the acceptance region.

Source of Error	RMS Magnitude	Unit
Cavity X, Y displacement	0.5	mm
Cavity Z displacement	1	mm
Cavity tilt	5/5/5/1/1	mrad
Cavity roll	5	mrad
Solenoid X, Y displacement	0.5	mm
Solenoid Z displacement	1	mm
Solenoid tilt	1	mrad
Solenoid roll	5	mrad
Quadrupole X,Y displacement	0.25	mm
Quadrupole Z displacement	1	mm
Quadrupole tilt	1	mrad
Quadrupole roll	1	mrad
Cryomodule X,Y displacement	0.3	mm
Cryomodule tilt	0.05	mrad

Error Study

Individual Errors

- All the errors were applied separately to study the sensitivity of linac for individual error.
- 50 seeds were executed with 100k initial particles for each configuration of error.



RMS relative emittance dilution in transverse and longitudinal plane as a function of displacement and tilt errors. It should be noted from the fig., displacement errors have worst impact on emittance in comparison to tilt errors. In some of the cases e.g. quadrupole tilt errors, emittance dilution was seen decreasing as the introduced error was increased.

Cryo-Module Errors

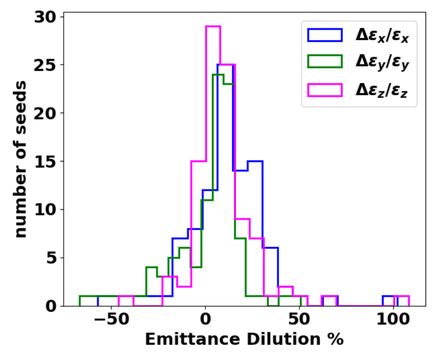
- Misalignment error in a cryo-module introduces systematic error and affects all the elements within.
- A displacement error shifts all element by same amount while tilt error rotates them about cryomodule centre.

RMS	CM only		CM+Random	
	Disp.	Tilt	Disp.	Tilt
$\Delta\epsilon_x/\epsilon_x(\%)$	1.71	0.24	14.32	1.16
$\Delta\epsilon_y/\epsilon_y(\%)$	0.5	0.3	10.92	0.93
$\Delta\epsilon_z/\epsilon_z(\%)$	0.98	0.21	8.58	0.94

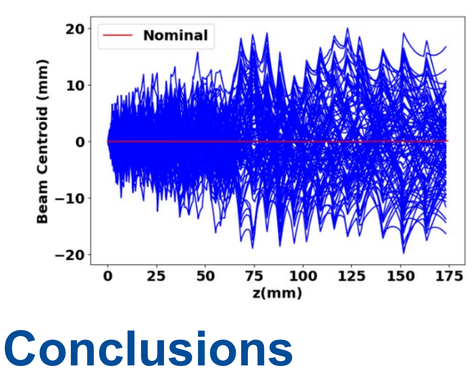
First, only cryomodule tilt and disp. Errors were applied. Later for a more realistic case, individual random errors were also added on top of cryo-module errors

Combined Errors

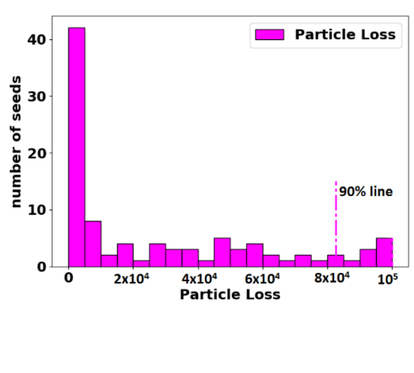
- All the nominal misalignment errors from the table were applied together and effect on the beam dynamics was observed.
- A set of 100 seeds were simulated with 100k initial particles.
- No correction scheme was used in the simulations.
- Centroid trajectory of the beam for all the seeds was plotted below. Maximum amplitude of centroid motion was ~18 mm.



In the present histogram of relative emittance dilutions in x,y and z, most number of seeds exhibit large rms emittance dilution ~20% in transverse and ~17% in longitudinal plane.



Beam Centroid Trajectory when combined errors are applied. Red line shows beam centroid when no error is applied.



A distribution of particle loss among 100 seeds was also plotted in the Fig. For this configuration of errors, 50% of the seeds lose >10 % of the particle.

Conclusions

- Large scale computation was done using Fermilab grid.
- Displacement errors have more detrimental effect of emittance when compared to tilt errors.
- Cryo-module errors were applied in the linac.
- When all the errors were applied simultaneously, most of the seeds show heavy losses. A suitable correction scheme will be developed in further study.

References

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