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BEAM DYNAMICS STUDY OF PIP-II SUPERCONDUCTING LINAC IN THE PRESENCE OF MISALIGNMENT ERRORS*

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Abstract

The Proton Improvement Plan (PIP)-II is a proposed high intensity proton facility being developed at the Fermilab. The PIP-II is primarily based on construction of a new superconducting radio frequency (SRF) linear accelerator (linac) that would deliver an average beam current of 2mA with output energy up to 800 MeV. The linac performance is mainly determined by beam sensitivity against various component errors. These errors trigger not only emittance dilution but also a beam loss in worst cases. This paper discusses effects of component misalignments on the beam and presents alignment budget for the PIP-II SRF linac.

INTRODUCTION

'Proton Improvement Plan (PIP)-II' is second stage of upgrades being planned to perform at existing accelerator complex at Fermilab. The PIP-II is devised to enable the Fermilab accelerator complex to deliver a beam power in excess of mega-watt (MW) on target at the initiation of Long Baseline Neutrino Facility [1]. This in turn, requires construction of a new Continuous Wave (CW)-compatible SRF linac. The PIP-II SRF linac will deliver H^- ions beam with a final kinetic energy of 800 MeV and an average current of 2 mA endowed with a special and flexible time structure to satisfy diverse experimental needs. A detailed description of the PIP-II linac was presented elsewhere [2].

Being an SRF ion accelerator, PIP-II is required to be operated under 1W/m of stringent beam loss criteria to avoid wall activation. To achieve this target, emittance growth in the linac must be controlled within a specified limit. A major cause of unwarranted emittance growth is the misalignment of beam line elements with respect to survey line [3]. Impact on beam dynamics due to misalignment errors is studied in the design phase itself. In this paper, misalignment errors were introduced into cavities and magnets of PIP-II SRF linac and effect on beam dynamics was studied.

PIP-II SRF Linac Description

The beam acceleration occurs mainly in the SRF linac that utilizes five families of superconducting cavities to accelerate the H^- ion beam from kinetic energy of 2.1 MeV to 800 MeV. Based on these families, the SRF linac is segmented into five sections i.e. Half Wave Resonator (HWR), Single Spoke Resonator (SSR) 1 & 2, Low Beta (LB) and High Beta (HB). Number of cryomodules (CM) and their configurations in each section are summarized in Table 1. Note that superconducting solenoids are used in HWR, SSR1 and SSR2 sections while warm quadrupole doublets are utilized in LB and HB sections.

Table 1: Numbers of elements and energy range in each section of the PIP-II SRF linac.

Section	CM	Cav/Mag per CM	Energy (MeV)
HWR	1	8/8	2.1-10
SSR1	2	8/4	10-32
SSR2	7	5/3	32-177
LB	9	4/1*	177-516
HB	4	6/1*	516-833

* one warm quadrupole doublet located between cryomodules in LB and HB sections

MISALIGNMENT ERRORS

For PIP-II linac, alignment budget for displacement, tilt and roll errors in beamline elements is presented in Table 2. Displacement is defined as a shift in the element position along vertical, horizontal or longitudinal directions. Tilt and roll are rotation of the element from centre about vertical/horizontal and longitudinal axis, respectively. The magnitude of errors in the table are root mean square (RMS) values of the corresponding gaussian error distribution.

Table 2: Standard alignment budget for PIP-II linac.

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

Setup

In the present study, misalignment error was introduced in

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the cavities and magnets with respect to their nominal position in the beam line. A set of random displacement and tilt errors were applied with Gaussian distribution in beam dynamics code TraceWin[4]. Following initial emittances in the Table 3 were used at the entrance of PIP-II SRF linac.

Table 3: Nominal emittances at linac entrance and exit.

Parameters	Nominal Values	
	Entrance	Exit
ϵ_x (π mm – mrad)	0.20	0.25
ϵ_y (π mm – mrad)	0.20	0.29
ϵ_z (π deg – MeV)	0.064	0.059

To obtain a good statistical average, a large number of linacs with different pattern (seeds) of random errors were simulated.

Large Scale Computing

To execute the large number of simulations in parallel, computing grid at Fermilab was used [5]. For a test case, simulations for a set of 100 seeds with 100k initial particles were launched on the grid. A histogram of completing time for seeds was plotted in the Fig. 1. Time in this figure includes waiting time in the que and processor runtime.

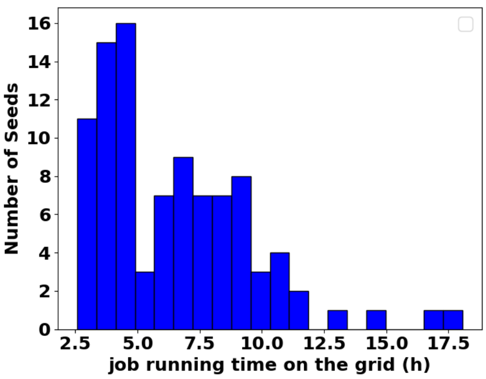

Figure 1: Time taken by the seeds to complete the simulation successfully on the grid.

Relative Emittance Dilution

Relative emittance dilution $\Delta\epsilon_i/\epsilon_i$ with respect to the nominal emittance at the linac output in plane *i,* can be defined as,

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

Where $\epsilon_{i,error}$ and $\epsilon_{i,nominal}$ are normalized emittances at the linac output for the case when error is applied and nominal case, respectively. Nominal emittances at linac output were shown in Table 3.

ERROR STUDY

In the present study, 50 seeds with 100k initial particles were executed for variety of errors. In the first step, all the errors were applied separately to estimate the sensitivity of beam parameters against specific error. Later, all the standard errors from Table 2 were applied together, and a combined effect was observed on the beam parameters.

Individual Errors

RMS Emittance dilution in transverse and longitudinal plane was plotted as a function of displacement and tilt errors as shown in Fig. 2. Figure 2(a) and 2(b) belong to cavity misalignment errors, Fig. 2(c) and 2(d) are due to quadrupole errors and solenoid errors are shown in 2(e) & 2(f). The magnitude of errors shown on the x-axis in the Fig. 2 are RMS values.

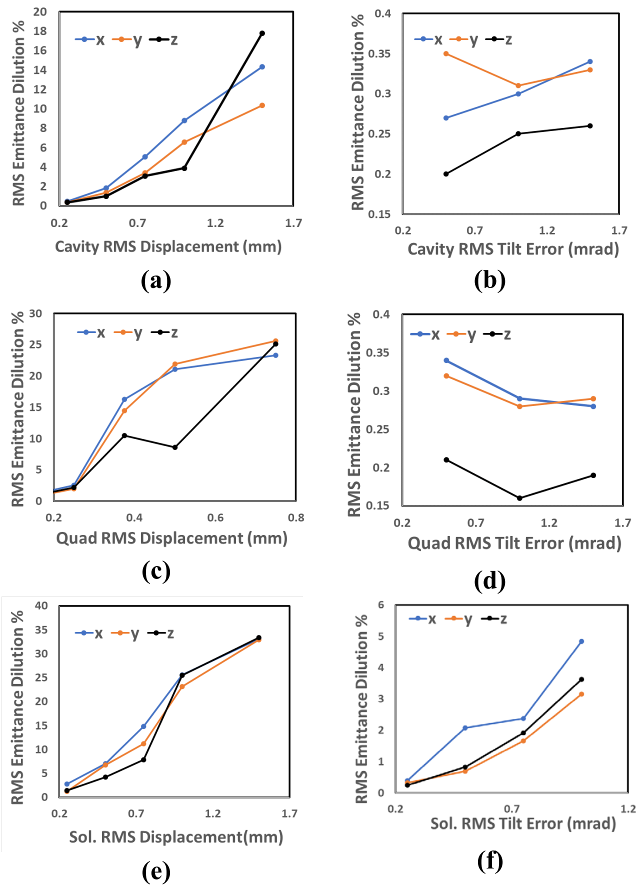

Figure 2: RMS emittance dilution ($\Delta\epsilon_i/\epsilon_i$) in transverse and longitudinal plane as a function of displacement and tilt errors.

It should be noted from the Fig. 2, 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.

Cryomodule Misalignment Errors

Any misalignment error introduced in a cryo-module affects all the elements within. A displacement error shifts all element by same amount while tilt error rotates them about cryomodule centre. Cryomodule misalignment introduces a systematic error in the study. In our calculations, cryomodule displacement and tilt errors were applied on the magnets and cavities. Relative emittance dilution due to the cryomodule misalignment error was estimated and shown in Table 4. To simulate a more realistic case, individual random errors of the beam line elements were also added on top of cryo-module errors. The results are presented in Table 4.

Table 4: RMS emittance dilution due to cryomodule displacement and tilt errors.

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

Combined Errors

All the misalignment errors from Table 2 were applied together and effect on the beam dynamics was observed. A set of 100 seeds were simulated with 100k initial particles in each case. No correction scheme was used in the simulations. Fig. 3 shows centroid trajectory of the beam for all the seeds. The centroid trajectory for the nominal case is also plotted red color. Maximum amplitude of centroid motion was ~18 mm.

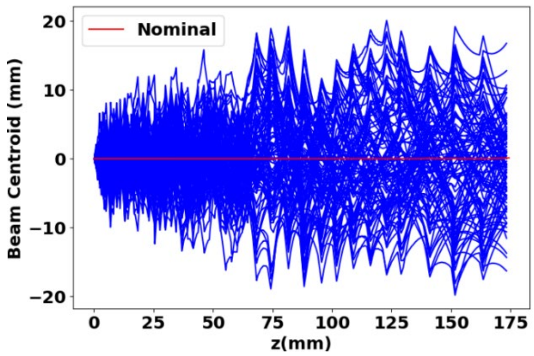

Figure 3: Centroid trajectory for all the seeds when all the errors were applied simultaneously according to Table 2.

A histogram of relative emittance dilution in transverse and longitudinal planes is plotted in Figure 4. Most number of seeds exhibit large rms emittance dilution ~20% in transverse and ~17% in longitudinal plane. A distribution of particle loss among 100 seeds was also plotted in the Figure 5. For this configuration of errors, 50% of the seeds lose >10 % of the beam.

CONCLUSIONS

Error calculations invlove large scale computation which was carried out on the grid using TraceWin. Introduction of invidual errors shows that displacment errors are more dangerous than the tilt errors. The cryomodule errors were also applied to check the linac robustness against the cryomodule errors. Beam parameters were checked for the case when all the errors were applied simultaneously. In this case, most of the seeds show that beam passes through the linac with heavy losses. For this case, a suitable correction scheme will be devised in further study to control the beam.

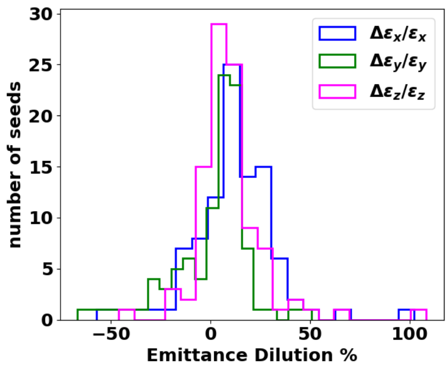

Figure 4: Histogram for relative Emittance dilution.

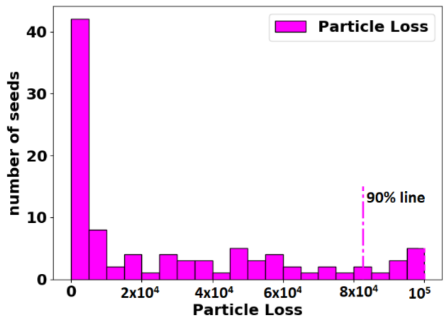

Figure 5: Distribution of particle loss in 100 seeds with random distribution of misalignment errors as shown in Table 2.

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