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OPTIMIZATION OF SUPERCONDUCTING LINAC FOR PROTON IMPROVEMENT PLAN-II (PIP-II)*

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Abstract

PIP-II is an essential upgrade of the Fermilab complex that will enable the world's most intense high-energy beam of neutrinos for the international Deep Underground Neutrino Experiment at LBNF and support a broad physics program at Fermilab. Ultimately, the PIP-II superconducting linac will be capable of accelerating the H^- CW beam to 800 MeV with an average power of 1.6 MW. To operate the linac with such high power, beam losses and beam emittance growth must be tightly controlled. In this paper, we present the results of global optimization of the Linac options towards a robust and efficient physics design for the superconducting section of the PIP-II linac. We also investigate the impact of the nonlinear field of the dipole correctors on the beam quality and derive the requirement on the field quality using statistical analysis. Finally, we assess the need to correct the quadrupole focusing produced by Half Wave, and Single Spoke accelerating cavities. We assess the feasibility of controlling the beam coupling in the machine by changing the polarity of the field of linac focusing solenoids

INTRODUCTION

The superconducting section of the PIP-II linac [1] aims to deliver a 2 mA (average current), 800 MeV, H^- beam using five distinct families of superconducting (SC) accelerating cavities accompanied by SC solenoids and normal conducting quadrupoles for transverse confinement. At such a high beam power, a meticulous, global optimization of the lattice parameters is essential to avoid transmission loss and beam quality deterioration through emittance growth, particularly at lower energies where the particle dynamics is primarily driven by nonlinear space-charge forces. Here we present the results of a comprehensive lattice optimization study undertaken to ensure a reliable, efficient, and robust physics design through a stable region of operation in the stability chart [2] with an adiabatic variation in the phase advances while keeping the structure phase advances below 90^0.

Apart from the beam degradation caused by the nonlinear space-charge forces at high intensities, the dipole corrector's nonlinearities [3,4] and asymmetric transverse RF defocusing produced by the spoke cavities [5–9] can affect the evolution of beam quality along the linac. Therefore, a thorough statistical analysis was performed to investigate the effect of the dipole corrector's nonlinearity on transverse emittance growth, and an upper limit on the uniformity of the field integral was established for an acceptable beam quality throughout the linac. The SC section of the PIP-II linac uses SC solenoids, guiding a symmetric focusing; therefore, any deviation from a symmetric nature in the transverse (x-y) plane is disfavored. However, the central conductor used in single spoke cavities introduces an asymmetric RF field, and therefore the beam suffers from asymmetric RF defocusing in x and y directions. The asymmetry produced by these cavities was investigated, and compensatory mechanisms using the solenoid current polarity and quadrupolar field generated by the pair of dipole corrector coils with appropriate configurations were compared for efficient asymmetry compensation while keeping minimal coupling between the two transverse planes and also reducing the cryomodule (CM) complexities through minimization of compensating remedies and related power supplies.

LATTICE OPTIMIZATION

We considered the existing physics design of the PIP-II linac with revised CM lengths and performed detailed optimization studies to minimize emittance growth and mitigate the collective resonances causing noticeable emittance exchange between longitudinal and transverse planes, as shown in Figs. 1(c) and 1(d). We performed a comprehensive analysis to quantify the impact of every accelerating and focusing element on beam behavior along the linac and adopted a tuning algorithm to minimize the emittance growth and halo development in all three planes. We determined to operate near a $k_z/k_{x,y} = 1.3$, and therefore, the solenoid fields were adjusted to satisfy the chosen operating point in the Hoffman chart while keeping a smooth phase advance transition and the structure tune per period below 90^o. Comparing

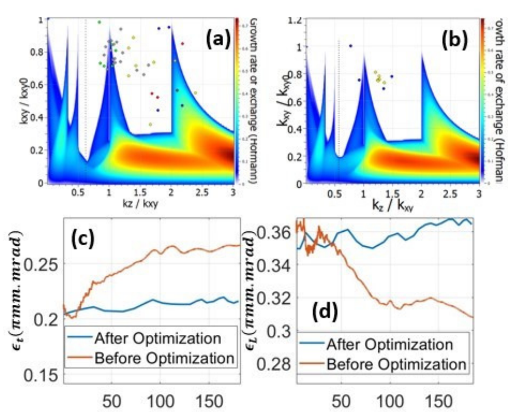

Figure 1: (a) Stability chart before optimization, (b) Stability chart after optimization, (c) Transverse normalized rms emittance, (d) Longitudinal normalized rms emittance.

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Figs. 1(a) and 1(b) suggests that the optimized tuning for the PIP-II linac demonstrates a noteworthy resonance-free operation without any inter-planer emittance exchange, as shown in Figs. 1(c) and 1(d). Our efforts toward eliminating parametric resonances from the lattice significantly reduce the transverse emittance growth from 30% to 3.4%. With a resonant-free operation in the optimized lattice, we do not observe the decrease in the longitudinal emittance because of emittance exchange; however, it shows an insignificant growth of 4.1% at the linac exit.

CORRECTOR COIL NONLINEARITY AND EMITTANCE GROWTH

The HWR and SSR section of the PIP-II linac uses horizontal and vertical pairs of dipole corrector magnets (Fig. 2(a)) to correct for the misalignment-induced orbit oscillations in the lattice. The field uniformity within the region of interest for these corrector coils plays a significant role in determining the beam quality due to the build-up of sextupole contribution with increasing nonlinearity. Figs. 2(b) and 2(c) exhibit an azimuthal variation of field along R and the dominant Fourier coefficient for a dipole corrector at 11% field integral non-uniformity and exemplify the existence of sextupole field components. The existence of a sextupole component can cause emittance growth and therefore needs to be minimized by estimating an upper bound on the field nonlinearity. We performed a detailed

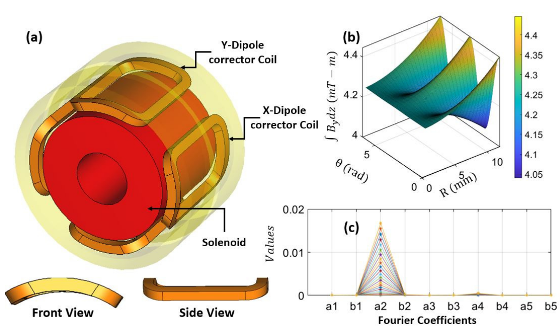

Figure 2: (a) Dipole corrector arrangement with solenoid and coil geometry, (b) Variation of field integral in R and θ plane, and (c) Fourier coefficient for varying radius from the center.

statistical study to model the cavities and solenoid misalignments within specified rms (σ) tolerances (Table 1) that are terminated at 2σ and followed a correction scheme using two corrector coils and two BPMs to minimize the resulting orbit offsets. Here we used 500 random seeds to generate the misalignment following a Gaussian distribution and used dipole correctors with a non-uniformity percent of 5%, 7%, 9%, and 11% within a 12 mm radius to perform orbit corrections and examined the obtained transverse emittances at the exit of the linac.

Our study shows an increase in the rms percentage emittance growth from 2% to 6.3%, for a non-uniformity percentage increase from 5% to 11%, and the growth pursues a

Table 1: Placement Requirements for Cavities and Solenoids

Parameters	**X (mm)**	**Y (mm)**	**Z (mm)**	**Pitch (deg)**	**Yaw (deg)**
HWR/SSR-1/SSR-2 Solenoid	0.5	0.5	1	1	1
HWR /SSR-1/SSR-2 Cavity	0.5	0.5	1	3	3

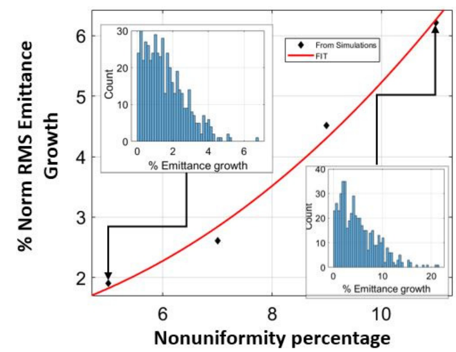

Figure 3: RMS percentage emittance growth with increasing field integral non-uniformity.

quadratic nature as shown in Fig. 3. However, the maximum percentage emittance growth reaches 6.5% and 20% for the mentioned percentage non-uniformity. Therefore a higher field integral non-uniformity can lead to significant degradation of the beam quality throughout the linac. Following the trend shown by the emittance growth, we determined to keep an upper limit on the dipole corrector field integral nonlinearity within 5% so that the emittance growth can be restricted to a maximum value of 6.3% with an rms at 2%.

ASYMMETRIC RF KICK AND MITIGATION SCENARIO

The PIP-II linac utilizes SSR cavities at lower velocities (from $\beta = 0.15$ to $\beta = 0.54$). Earlier studies for the PIP-II spoke cavities [5–9] suggest that the spoke cavity produces an asymmetric transverse quadrupolar defocusing that may lead to an asymmetric particle distribution in the transverse (x-y) plane. In this paper, we further examine this effect in the PIP-II linac, find an efficient scheme to compensate for it, and finally, derive the requirement for the compensation scheme.

We quantified the transverse splitting taking into account the transit-time factor and the synchronous phase of the beam, and explored methods to minimize it using the solenoid current polarities and the quadrupole fields generated by the corrector coils.

Our study shows that with a change in the current polarity of certain solenoids that are identified after considerable iterative optimizations, the x-y rms envelope splitting decreases, as shown in Figs. 4(b) and 4(c). But, a careful analysis of the beam matrix and the particle density distri-

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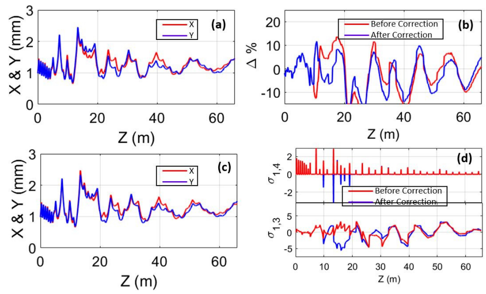

Figure 4: (a) Envelope evolution before solenoid compensation,(b) X-Y splitting percentage($\Delta\% = \frac{Y_{rms}-X_{rms}}{X_{rms}} \times 100$) , (c) RMS envelope after solenoid compensation, and (d)$\sigma_{1,3}$ and $\sigma_{1,4}$ variation along the linac.

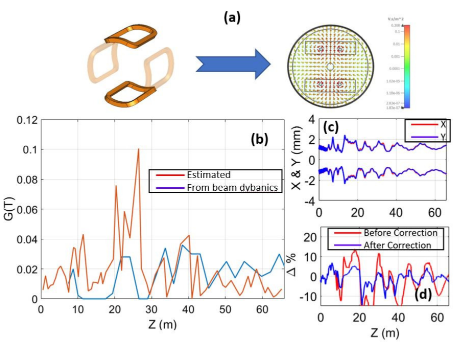

Figure 5: (a) Corrector coils and respective quadrupole field, (b) Quadrupole gradient integral, (c) RMS envelope evolution, and (d) x-y splitting percentage.

bution in coordinate space reveals that flipping the solenoid current polarity increases the x-y coupling (Fig. 4(d)), and therefore, the beam rotates with an elliptic profile giving a false impression of its symmetric nature.

With the limitations posed by the solenoid compensation approach, we examined the potential of utilizing the quadrupole field produced by the corrector coils with appropriate polarity. Figure 5(a) shows the pair of dipole corrector magnets and respective magnetic quadrupolar field profiles. The x-y envelope splitting was calculated using the scaled RF fields from the optimized cavities, the synchronous phase, and particle velocity to estimate the compensating quadrupole gradient integral, and the results were compared with the compensating gradient integral obtained through a fully three-dimensional particle tracking simulations. Figure 5(b) compares the calculated and obtained gradient integrals, which are in good agreement with each other. The use of the corrector magnets reduces the splitting percentage from 15% to 5% in the SSR-1 section and from 13% to 10% in the SSR-2 section, as shown in Figs. 5(c) and 5(d); however, the splitting remains within 5% for most of the linac. We calculated and compared the results before and after quadrupole corrections to establish the beam's transverse ellipticity reduction, and the results are shown in Fig. 6. Figure 6 demonstrates an overall reduction in the ellipticity after quadrupole correction. Although we could

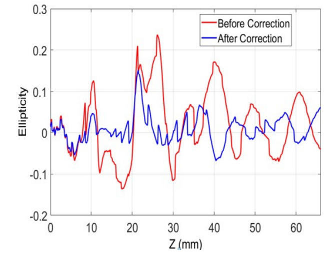

Figure 6: Beam ellipticity ($\frac{x-y}{x}$) in X-Y plane before and after splitting minimization.

achieve a significant reduction in the beam splitting, the compensation requires 50% of the correction strength; however, even without the quadrupole compensation, we observe a maximum ellipticity of 1.8, which has a negligible impact on the transverse emittance in the absence of other misalignments. Our study also shows that, in case of misalignment followed by orbit corrections, the splitting results remain unperturbed. With such a negligible effect of asymmetric defocusing on beam dynamics which can be corrected using the skewed quadrupoles in the high energy section of the linac, we need to decide on the employment of quadrupole compensation after comparing the gain with quadrupole compensation against the increase in CMs complexities that it brings through an increase in the number of power supplies and corresponding modification, and make the final decision.

CONCLUSION

A detailed lattice tuning was performed for the SC section of the PIP-II linac, and a significant reduction of 27% in transverse rms emittance growth was obtained. The final lattice design with optimized phase advances and carefully tuned elements produces an emittance growth of 3.4% and 4.1% in transverse and longitudinal planes, respectively.

We also performed a statistical study to investigate the effect of dipole corrector non-uniformity on emittance growth in the presence of cavity and solenoid misalignments followed by orbit corrections using the x and y pair of corrector coils. Our study indicates a quadratic dependence of emittance growth on the field integral non-uniformity, which we found to be acceptable within 5% for acceptable beam quality. Finally, we looked at the beam splitting caused by the asymmetric RF defocusing caused by spoke cavities. After a detailed comparison of different splitting minimization approaches, the use of the quadrupole fields generated by the corrector coils is found to be most effective and reduces the beam ellipticity to a great extent but at the cost of utilizing 50% of the corrector strengths. Our analysis also suggests that the splitting compensation has a minimal effect on the beam dynamics as the ellipticity even without compensation is nominal, and therefore a decision over the use of quadrupole compensation has to be taken considering the option of using the skewed quadrupole in the high energy section of the linac to completely eliminate the residual ellipticity.

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