

FINAL PHYSICS DESIGN OF PROTON IMPROVEMENT PLAN-II AT FERMILAB

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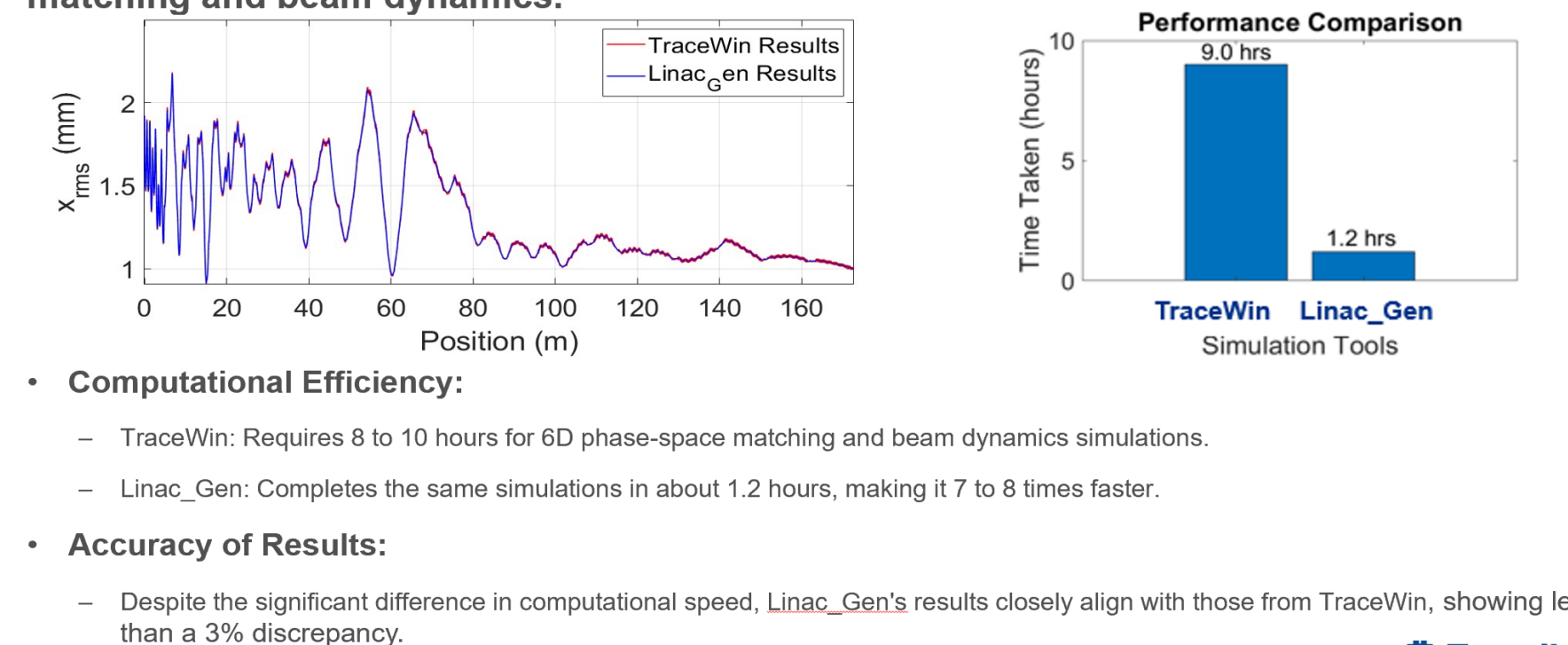
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ABSTRACT

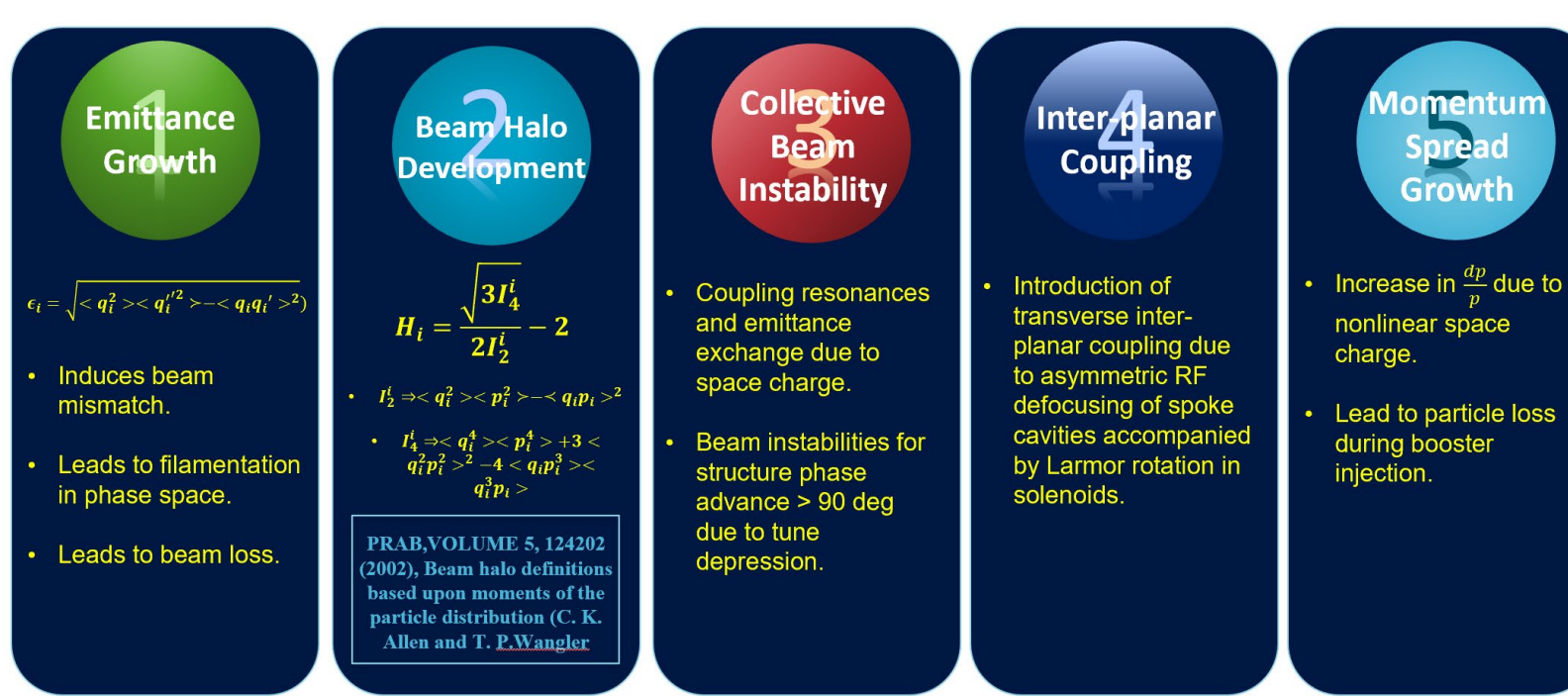
This paper presents the final physics design of the Proton Improvement Plan-II (PIP-II) at Fermilab, focusing on the linear accelerator (Linac) and its beam transfer line. We address the challenges in longitudinal and transverse lattice design, specifically targeting collective effects, parametric resonances, and space charge nonlinearities that impact beam stability and emittance control. The strategies implemented effectively mitigate space charge complexities, resulting in significant improvements in beam quality—evidenced by reduced emittance growth, lower beam halo, decreased loss, and better energy spread management. This comprehensive study is pivotal for the PIP-II project's success, providing valuable insights and approaches for future accelerator designs, especially in managing nonlinearities and enhancing beam dynamics.

PERFORMANCE ANALYSIS: TRACEWIN VS. LINAC_GEN

Evaluating the computational efficiency of TraceWin and Linac_Gen for 6D phase-space matching and beam dynamics.

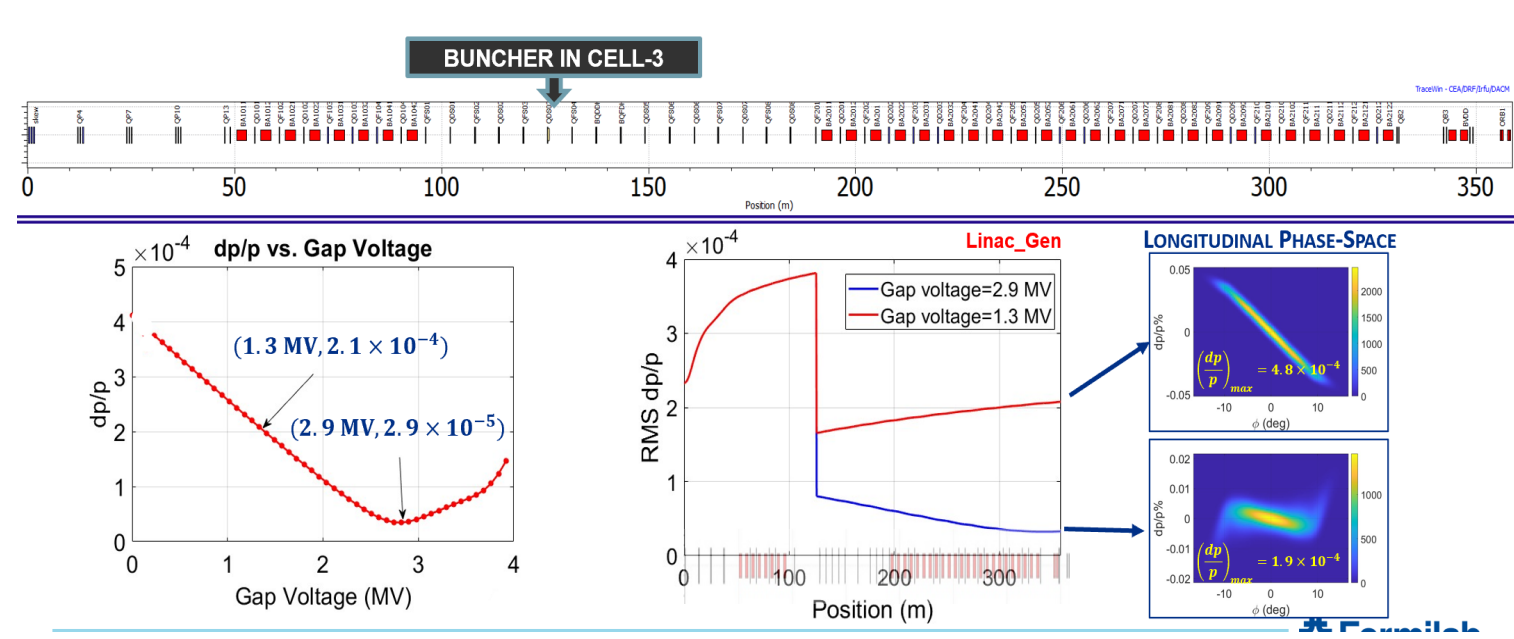


BEAM PHYSICS CHALLENGES



MOMENTUM SPREAD COMPENSATION

We placed the buncher cavity in the 3rd cell of the BTL and optimized its gap voltage to obtain the required as well as minimum momentum spread at the exit of the BTL.

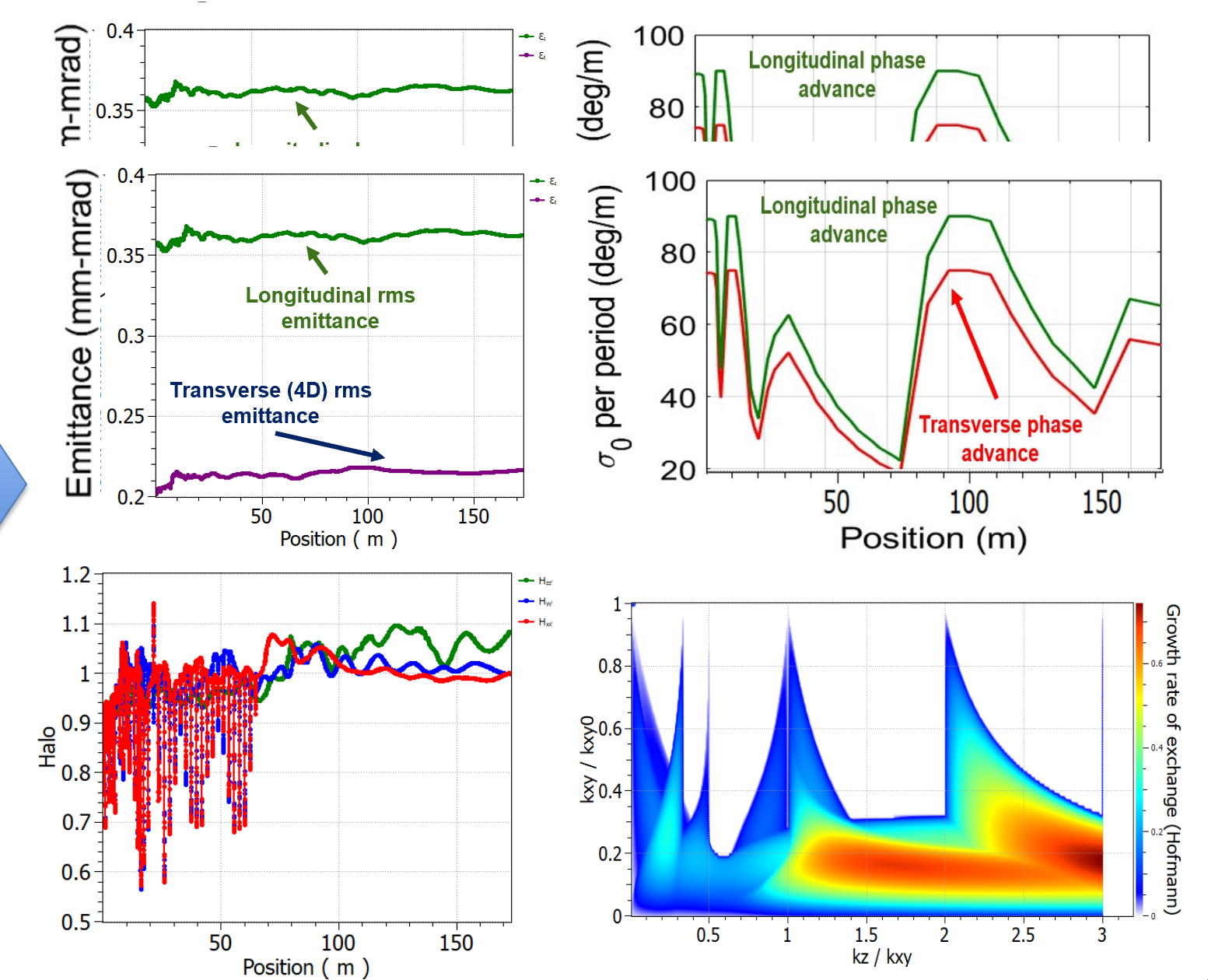
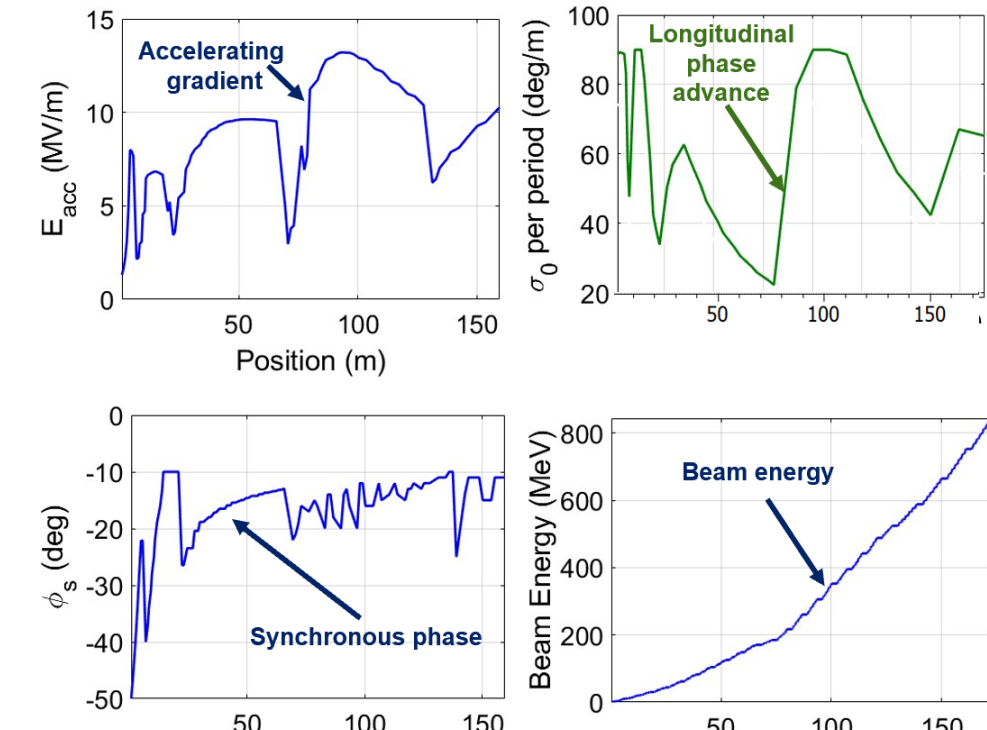


LONGITUDINAL DYNAMICS

Custom-developed code 'Linac_Gen' utilized for optimization.

- Considerations:
 - Structure Phase Advance: Kept at or below 90° .
 - Energy Gain Target: From 2.1 MeV to 800 MeV.
 - Accelerating Gradient: Not to exceed E_{max_cav} .

Cavity	Aperture (mm)	Effective Length (m)	Accelerating Gradient (MV/m)	β_{max}	β_{min}	R/Q (Ω)	Q_0
HR40	33	20.7	9.7	44.9	48.3	272	43
SSR1	30	20.5	10	38.4	58.1	242	84
SSR2	40	43.8	11.4	40	64.5	297	115
LHR60	80	70.3	16.9	40.3	74.6	341	157
HR650	118	106.1	18.8	38.9	73.1	610	200



DIPOLE CORRECTOR STUDIES

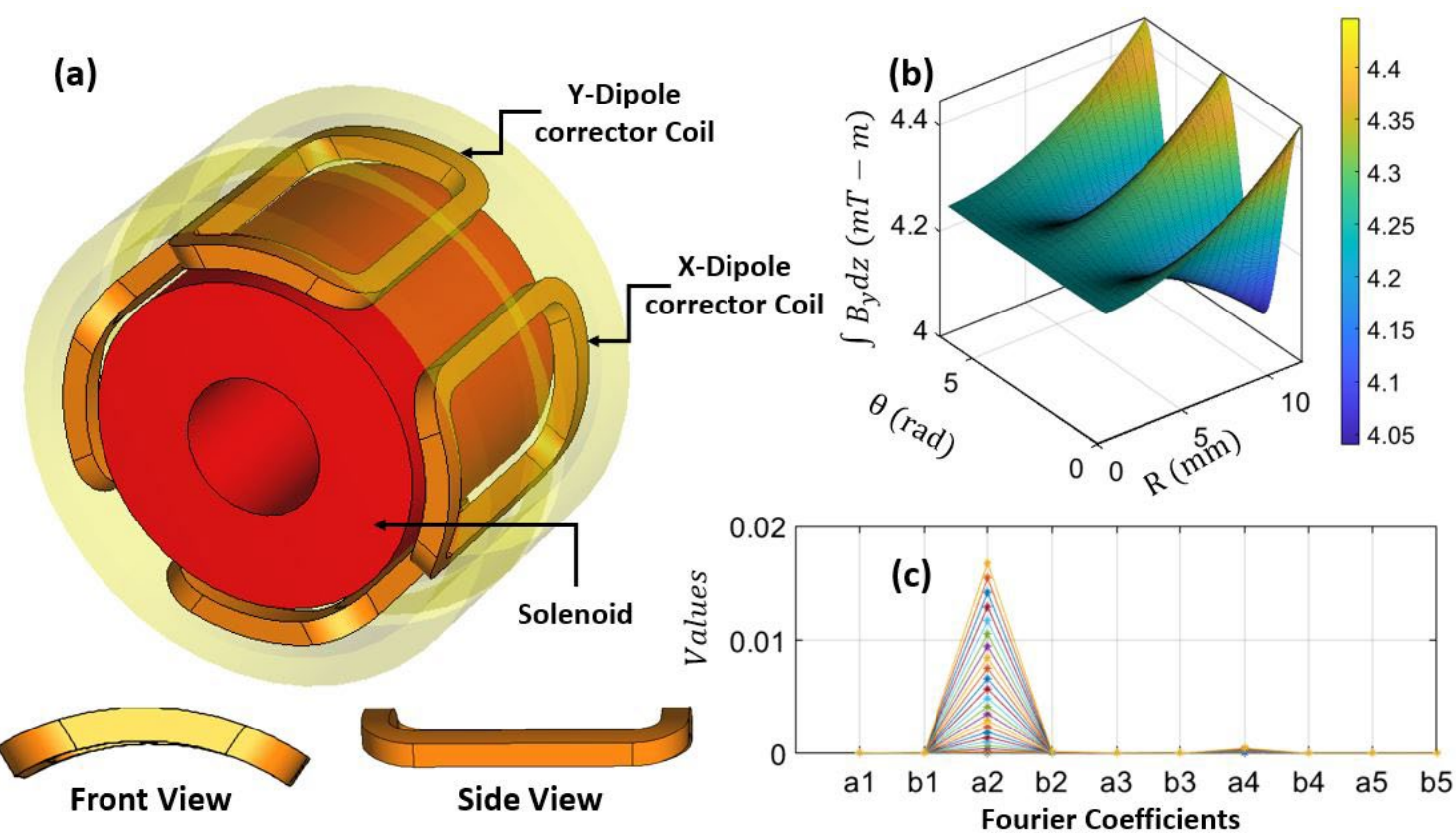


Fig.6: (a) Schematic of the solenoid and dipole corrector magnets used in SC section of PIP-II linac, (b) Radial and azimuthal variation of dipole corrector field integral, (c) Fourier coefficients obtained after Fourier fit of $\int B_x(r, \theta)$.

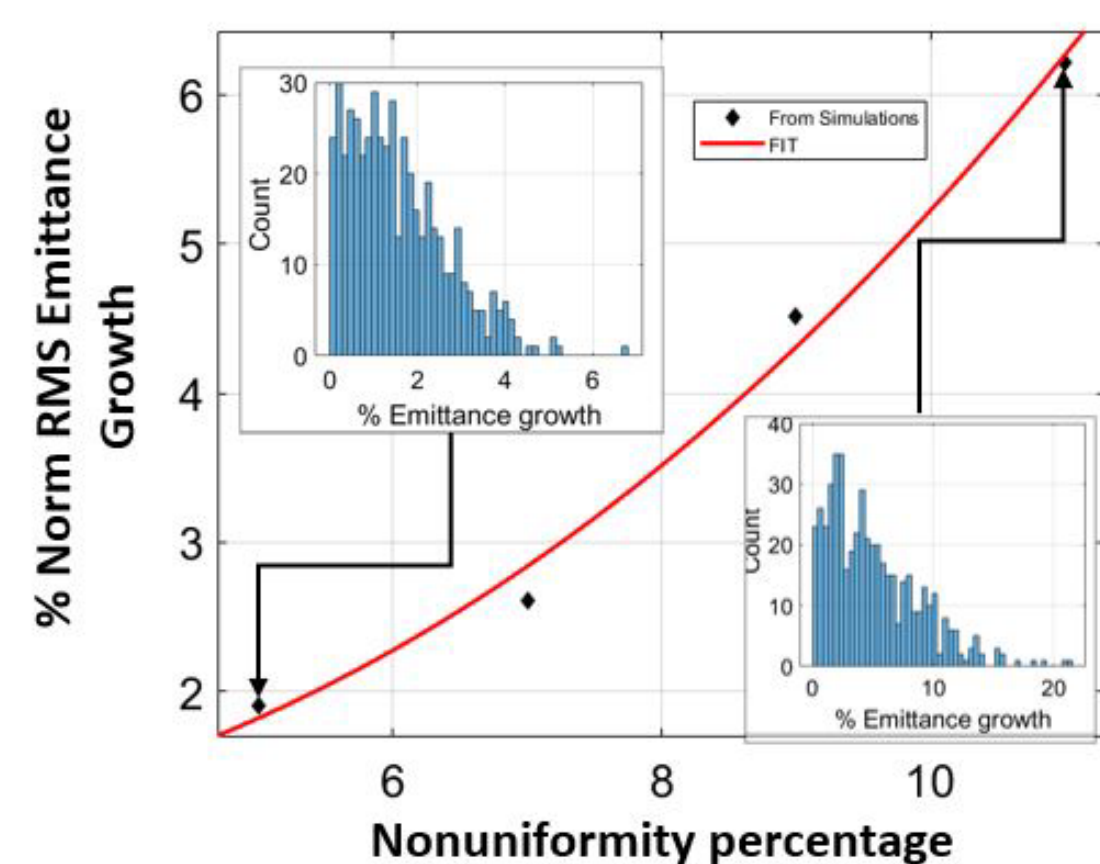


Fig.7: Quadratic variation of percentage emittance growth on dipole corrector field nonuniformity and %emittance growth distributions for statistical studies performed at 5% and 11% field nonlinearity.

ASYMMETRIC MOMENTUM KICK & MITIGATION STRATEGIES

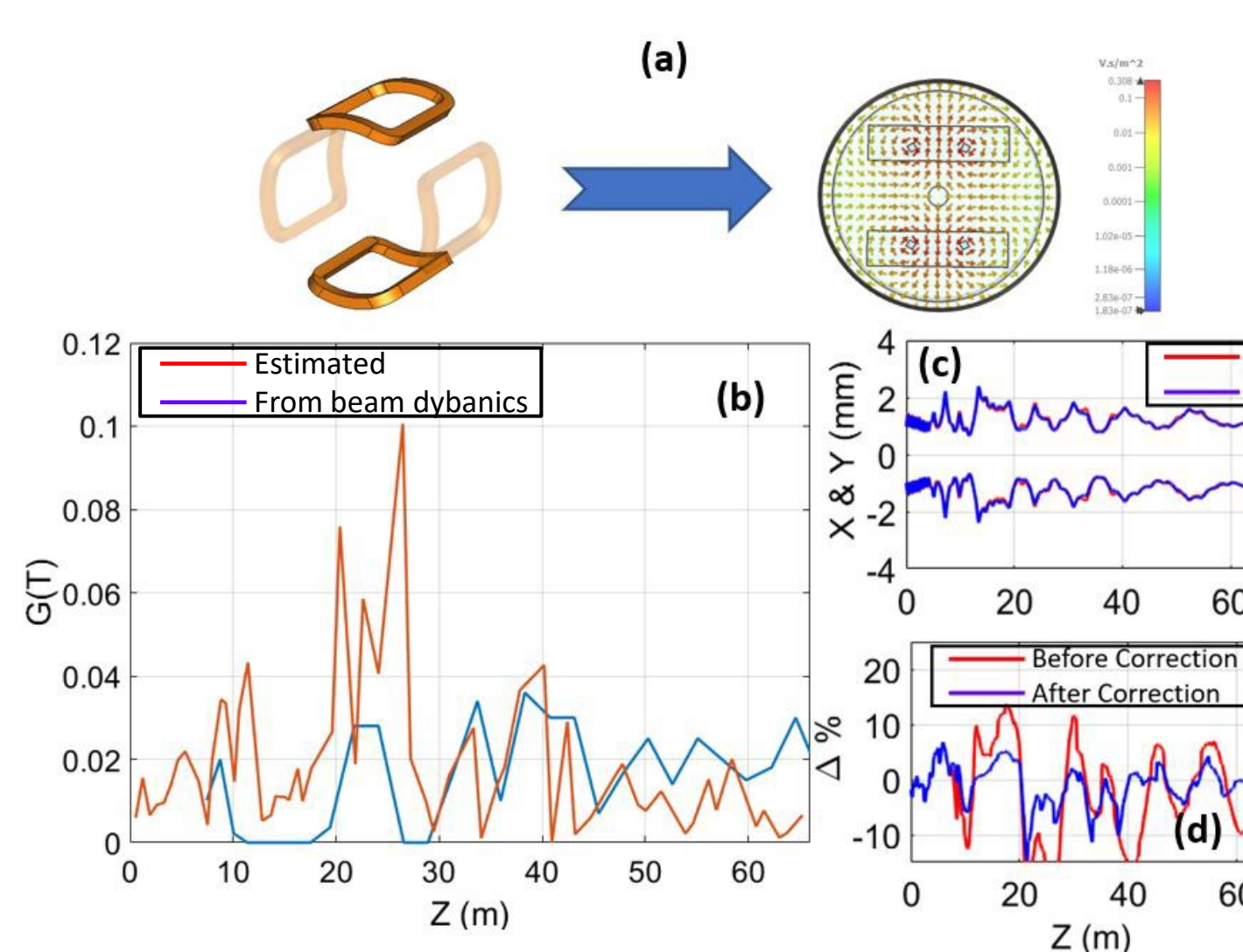


Fig.8: (a) Dipole corrector arrangement used to produce quadrupole field for splitting compensation and respective field pattern, (b) Estimated and obtained gradient integrals, (c) RMS envelope after compensation, and (d) Δ % before and after compensation.

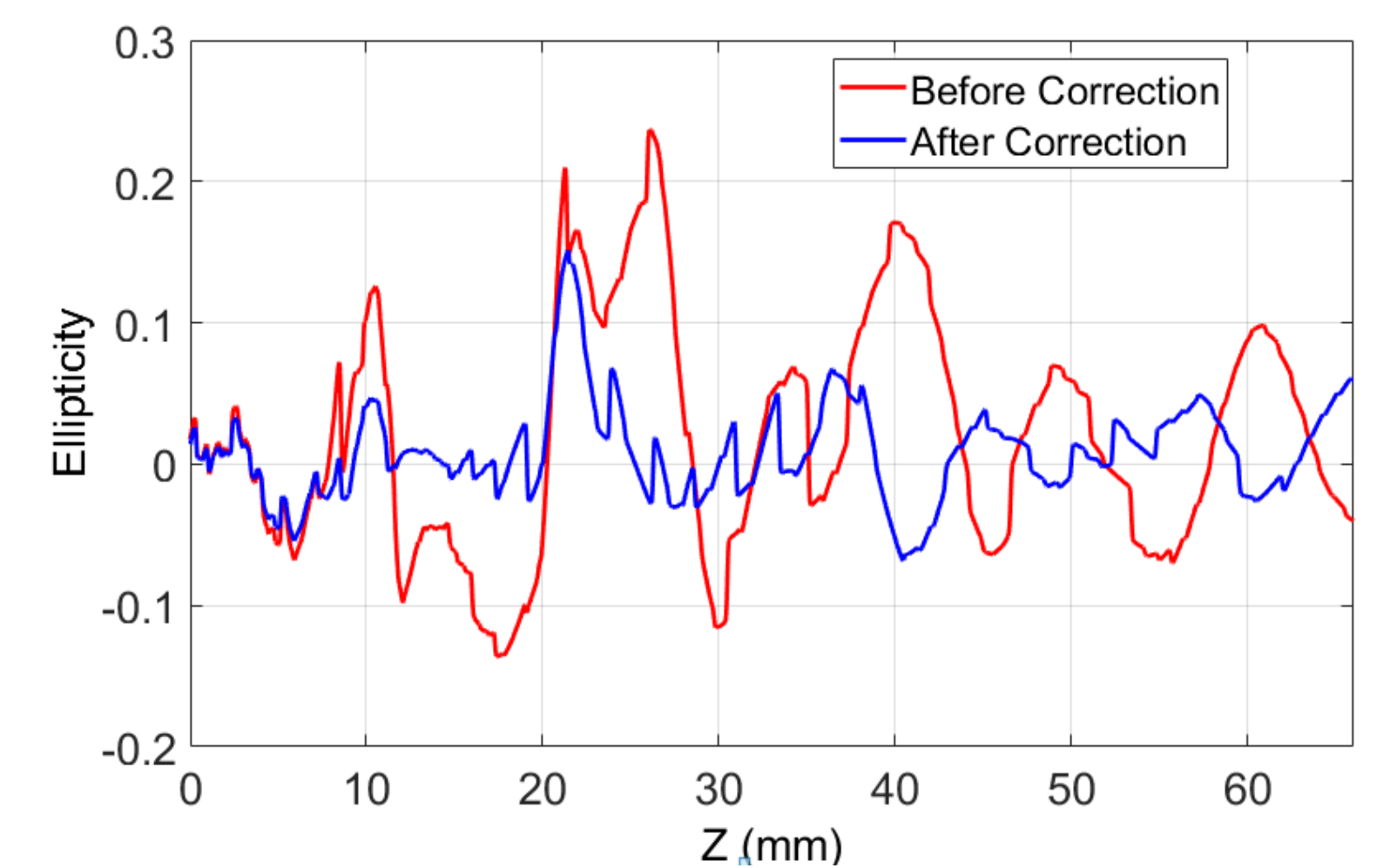


Fig.9: Beam ellipticity in coordinate space before and after compensation using the quadrupole fields/splitting% before and after compensation.

CONCLUSION

- The Physics design of the PIP-II SC linac was further optimized to obtain a negligible emittance growth of 3.5% at the exit of the linac.
- The effect of the dipole corrector's nonlinearity on emittance growth was investigated, and an upper limit of 5% on field integral uniformity is proposed for acceptable beam quality.
- The X-Y splitting due to asymmetric Rf fields is observed to have an unnoticeable effect on the beam quality. However, the effect can further be reduced using the quadrupoles fields obtained through corrector magnets with appropriate polarity. Using
- Developed 'Linac_Gen', a custom code for advanced longitudinal and transverse lattice design and beam dynamics with PIC algorithms.

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