SPACE CHARGE DOMINATED MOMENTUM SPREAD AND COMPENSATION STRATEGIES IN THE POST-LINAC SECTION OF PROTON IMPROVEMENT PLAN-II AT FERMILAB

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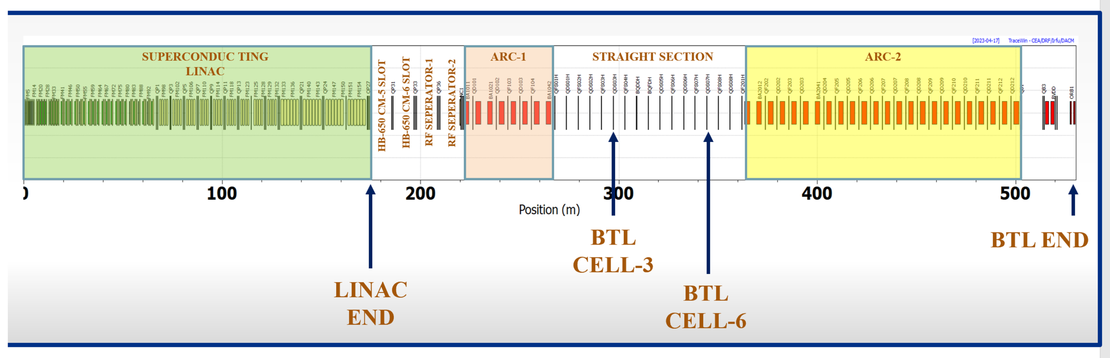
FERMILAB-POSTER-24-0047-PIP2.

ABSTRACT

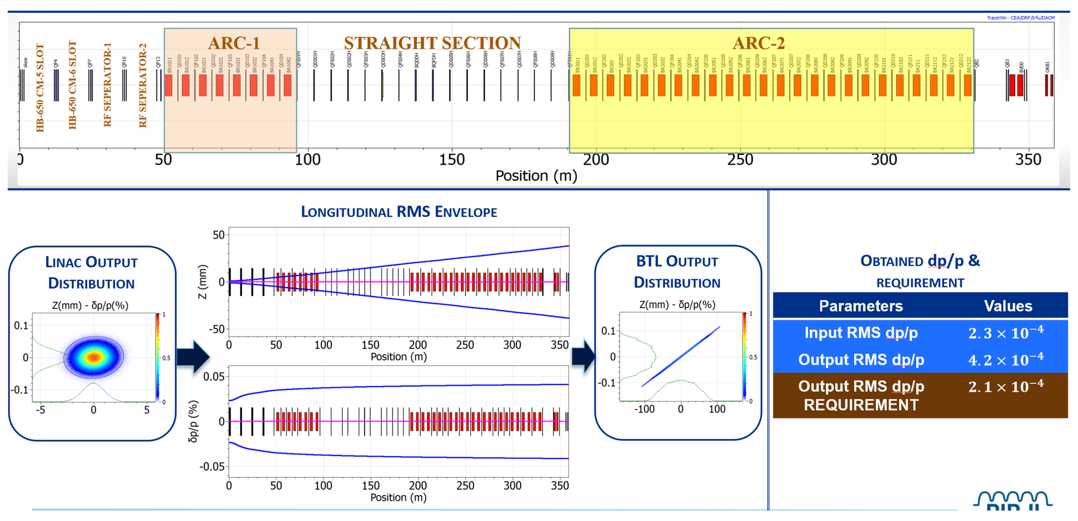
The upcoming Proton Improvement Plan-II (PIP-II), designated for enhancements to the Fermilab accelerator complex, features a Beam Transfer Line (BTL) that channels the beam from the linac exit to the booster. In the absence of longitudinal focusing beyond the superconducting linac, the beam experiences an elevated momentum spread, primarily due to nonlinear space-charge forces, surpassing the allowable limit of 2.1e-4. This study presents a detailed examination of the space-charge-induced momentum spread and outlines mitigative strategies. The investigation includes the fine-tuning of a de-buncher cavity, analyzed in terms of operating frequency, longitudinal location, and gap voltage, under both standard and perturbed beam conditions—specifically accounting for momentum jitter and energy variation. The impact of buncher cavity misalignments on the beam's longitudinal phase space is also assessed. The paper concludes by recommending an optimized cavity configuration to effectively mitigate the observed increase in momentum spread along the BTL.

PIP-II SC LINAC & BRAM TRANSFER LINE (BTL)

- Here we have marked the location of the critical point that will be considered throughout this energy spread minimization study.



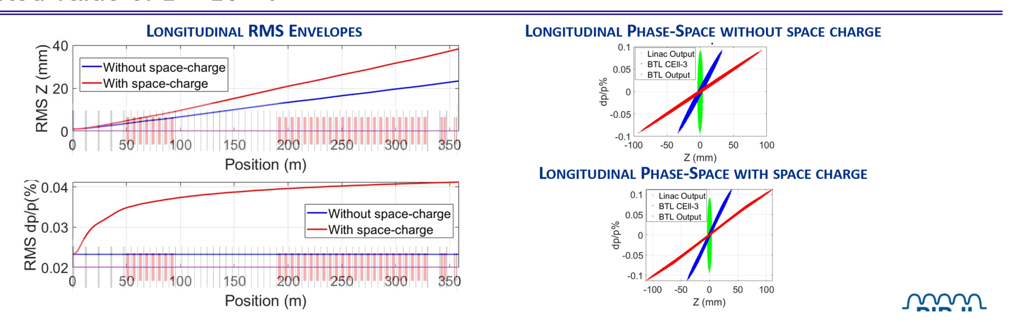
LONGITUDINAL DYNAMICS IN POST PIP-II LINAC & BTL



Parameters	Values
Input RMS dp/p	2.3×10^{-4}
Output RMS dp/p	4.2×10^{-4}
Output RMS dp/p REQUIREMENT	2.1×10^{-4}

KEY CONCERN

- Lack of longitudinal focusing after the Superconducting section of the PIP-II linac results in an increase in momentum spread along the BTL section driven by the beam's space charge.
- With space charge present, the rms dp/p at the exit of BTL is 4.2×10^{-4}, twice the desired value, while the maximum dp/p reaches 1.13×10^{-3}, surpassing the expected value of 1×10^{-3}.

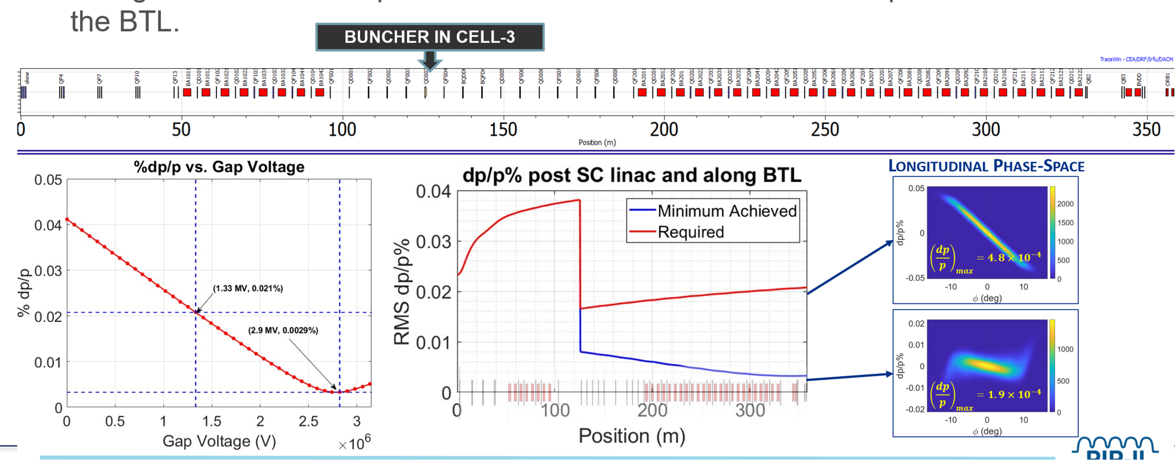


COMPENSATION STRATEGY

- Investigated the utilization of a 650 MHz buncher cavity in the Beam Transfer Line (BTL) to mitigate the increases in momentum spread at the end of the BTL.
- Based on space availability, two optimal placements for the buncher cavity were explored:
  - *-BTL CELL-6*
  - *-BTL CELL-3*
- Varied the cavity voltage to examine its impact on dp/p at the BTL's exit:
  - *-Placed the buncher the BTL.*
  - *-Determined the gap voltage necessary to achieve the minimum dp/p at the BTL's exit.*
  - *-Obtain the gap voltage to achieve the target dp/p.*
- The analysis considered the effects of nonlinear space charge forces.

BUNCHER CAVITY IN BTL CELL-3

- 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.



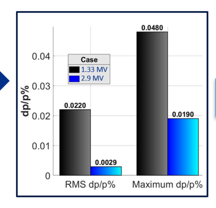
REQUIRED VS. MINIMUM MOMENTUM SPREAD

Required Momentum Spread & Gap Voltage

Parameters	Values
RMS dp/p%	0.021
Maximum dp/p%	0.048%
Gap Voltage	1.33 MV

Minimum Momentum Spread & Gap Voltage

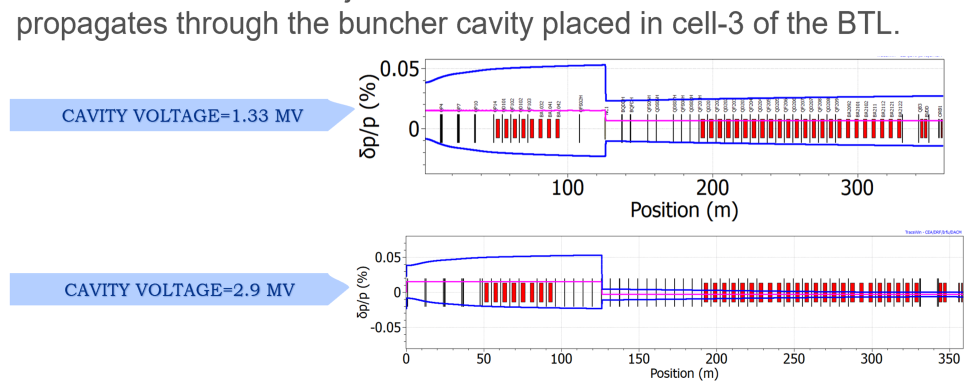
Parameters	Values
RMS dp/p%	0.0029%
Maximum dp/p%	0.019%
Gap Voltage	2.9 MV



- By positioning the buncher cavity in BTL cell-3, we achieved the desired rms dp/p of 2.1×10^{-4} at a gap voltage of 1.33 MV.
- By increasing the gap voltage from 1.33 MV to 2.9 MV, the rms dp/p can be further decreased to 0.29×10^{-4}, which is seven times lower than the required value.

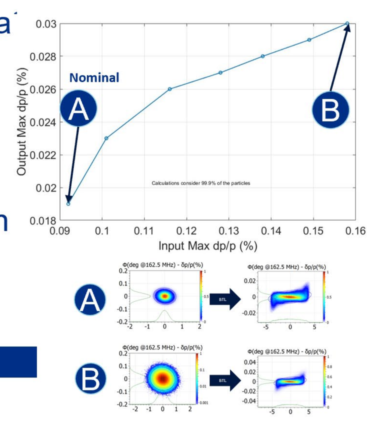
EFFECT OF BUNCHER CAVITY ON MOMENTUM JITTER

- In addition to the compensation of the momentum spread, the buncher cavity also reduces the momentum jitter present in the beam.
- We considered an initial jitter of 1.5×10^{-4} and observed its evolution as it propagates through the buncher cavity placed in cell-3 of the BTL.



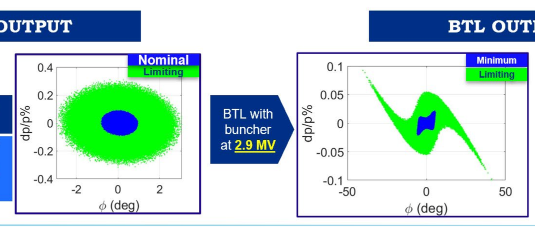
LONGITUDINAL TAIL & MOMENTUM COMPENSATION

- We examined the impact of the increased momentum tail at the linac exit on the momentum spead at the BTL output, with a buncher cavity placed in cell-3 of the BTL and optimized for the lowest dp/p.
- The assessment of the permissible longitudinal tail for booster injection reveals that a linac output distribution can accommodate a tail up to $\frac{dp}{p}=3.2\times10^{-3}$ can be used for booster injection.



LINAC OUTPUT

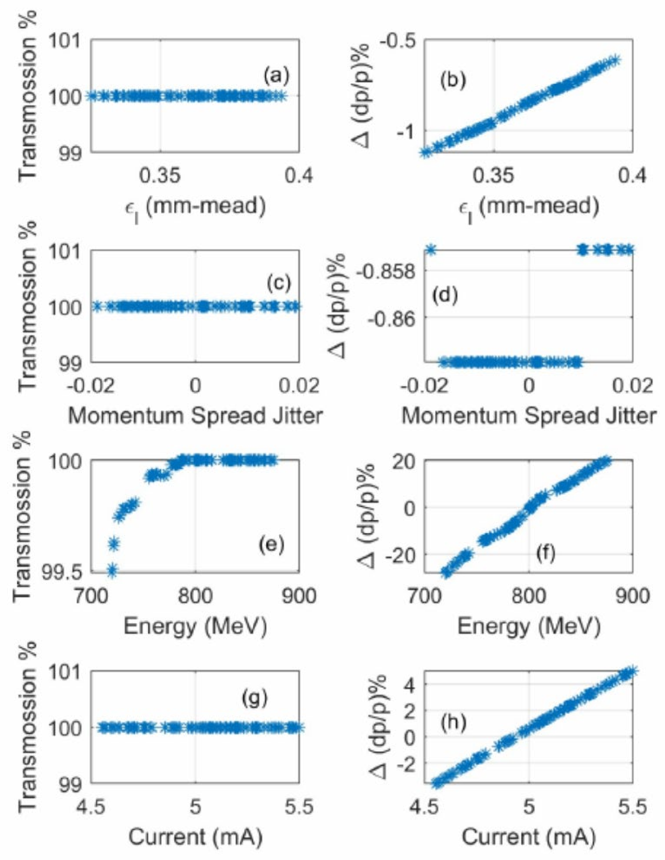
Parameters	Nominal Case	Limiting Case
RMS dp/p	2.3×10^{-4}	7.9×10^{-4}
Maximum dp/p	9×10^{-4}	32×10^{-4}



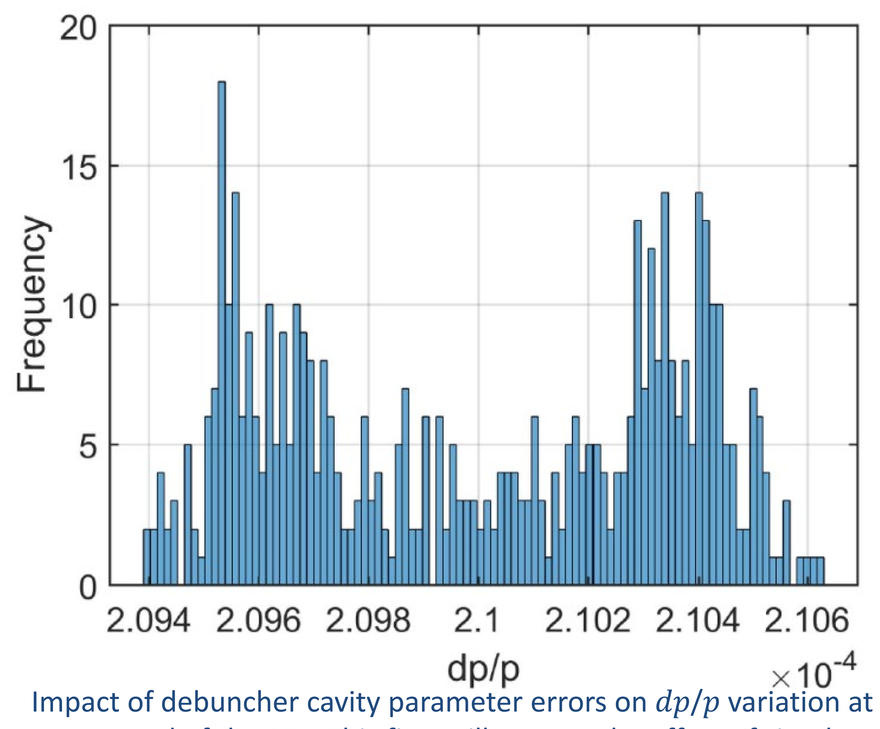
BTL OUTPUT

Parameters	Limiting case	Minimum case
RMS dp/p%	1.9×10^{-4}	2.9×10^{-5}
Maximum dp/p%	1×10^{-3}	1.0×10^{-4}

This poster has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.



Variability of beam transmission and momentum spread. (a, c, e, g) display the transmission percentage against variations in longitudinal emittance, momentum jitter, energy, and current. (b, d, f, h) illustrate the impact of these parameters on momentum spread at the exit of the BTL, indicating parameter sensitivity.



Impact of debuncher cavity parameter errors on dp/p variation at the upstream end of the BTL. This figure illustrates the effect of simultaneously introducing uniform random misalignment errors ΔX, ΔY, $\Delta Z = \pm4$ mm offsets, and a 5% error in both field amplitude and phase, across 500 simulation runs.

CONCLUSION

- The momentum spread along the BTL, predominantly influenced by space charge, can be offset by utilizing a buncher cavity positioned within the BTL.
- The gap voltage of the buncher cavity, located in cell-3 of the beam transfer line, has been optimized to achieve a momentum spread (dp/p) of 2.1×10^(−4) at a gap voltage of 1.3 MV.
- With the buncher cavity, there's potential to further reduce the momentum spread to 2.9×10^(−5)by elevating the gap voltage range from 1.33 MV up to 2.9 MV.
- The buncher cavity also compensates for momentum jitter present in the beam.
- Analysis of the longitudinal tail at the linac's exit for booster injection indicates a margin of 3.3 times the rms dp/p and 3.5 times the maximum dp/p.