Proton Beam Compression Studies in the Spallation Neutron Source for a 10 TeV Muon Collider

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Motivation

- Muons are promising candidates to use in a new collider to explore Beyond the Standard Model physics through higher energy collisions.
  - All of the beam energy is available for collision: 13-14 TeV p^+colliders at CERN LHC probing ~1 TeV energy scales due to synchotron radiation vs. 10 TeV μ^- colliders.
  - Less synchotron radiation: μ^- 200x heavier than e^-, $P \propto \left(\frac{E}{m}\right)^4$.

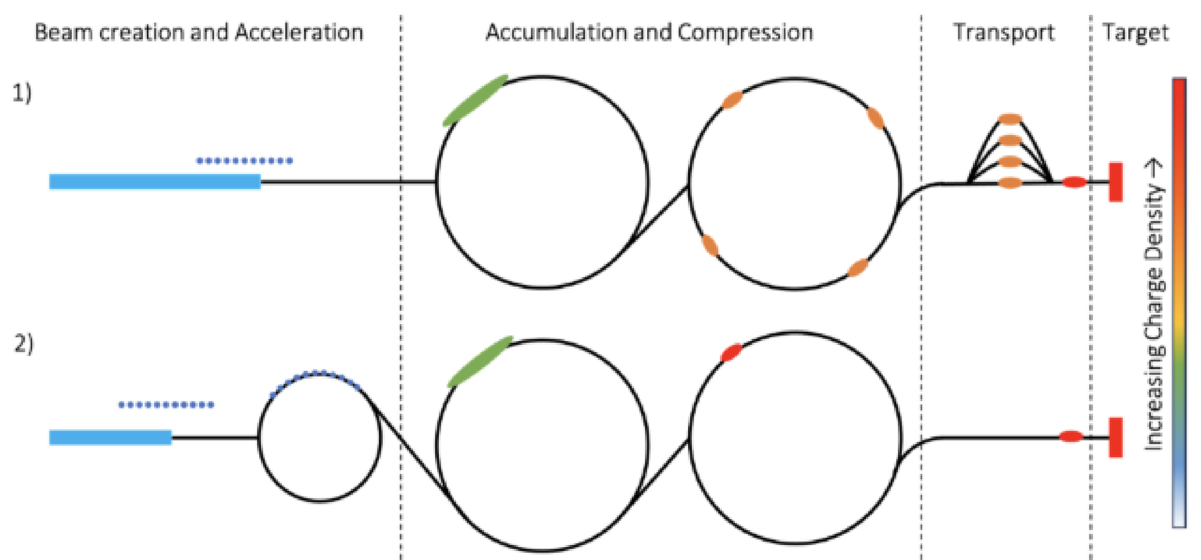
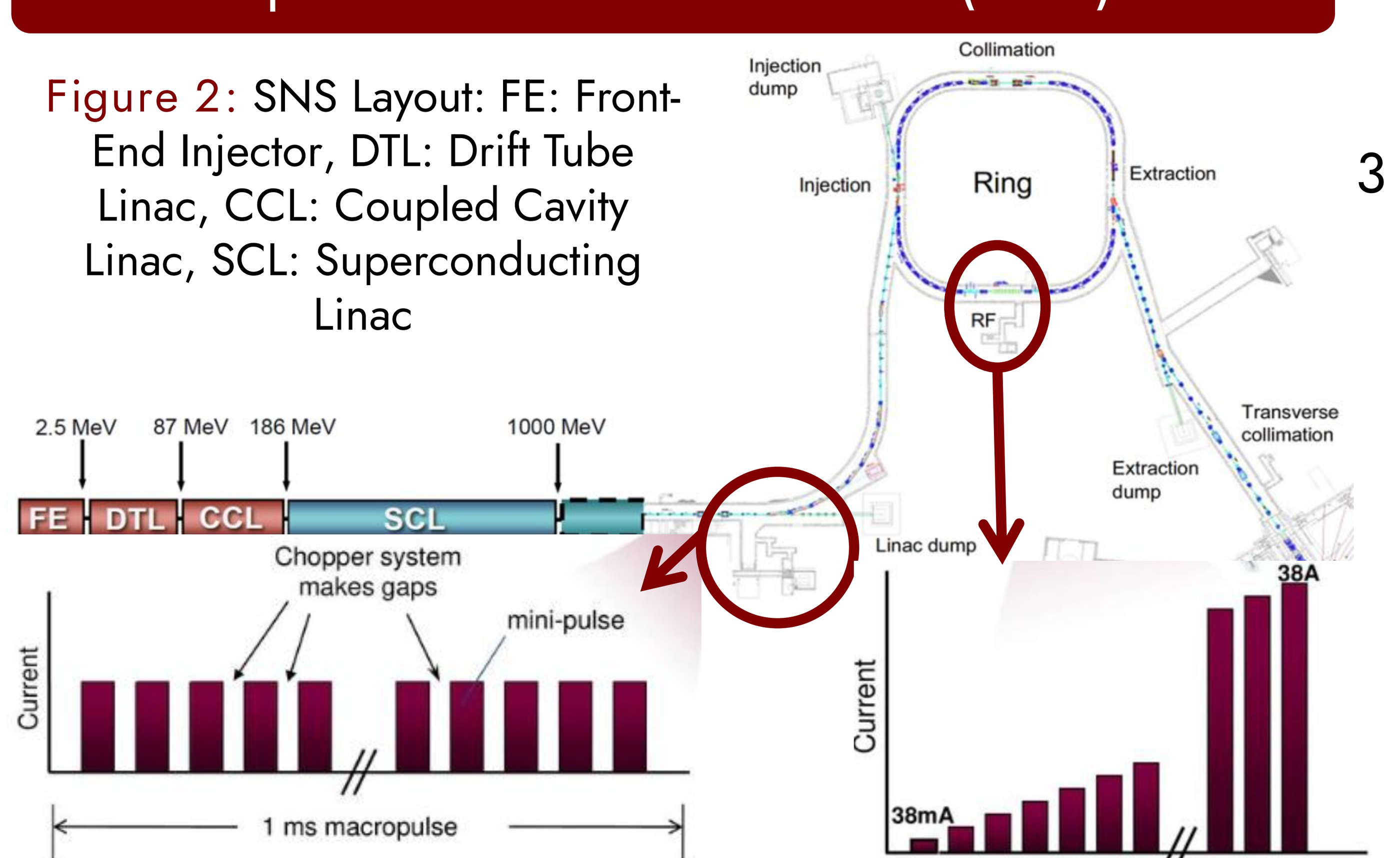


Figure 1: Muon Collider (MuC) Proton Driver

- MuC requires a compression ring with finely tuned rf cavities to shrink the beam in time while increasing energy spread to obtain short, intense proton bunches with a desired bunch length of 2 ns rms width.
- No operational accelerators that can perform these experiments at the relevant space charge intensity other than world's highest power proton beam (2.4 MW nominal) in SNS @ ORNL.

Spallation Neutron Source (SNS)

Figure 2: SNS Layout: FE: Front-End Injector, DTL: Drift Tube Linac, CCL: Coupled Cavity Linac, SCL: Superconducting Linac



Project Goals

Goal: To study the collective effects in the extreme space charge regime found in high-intensity accelerators like MuC through looking at bunch compression of 350 ns rms width bunches in SNS.

1. Experiment: Collect initial data on various beam accumulation, bunch compression, and beam storage schemes in the SNS Accumulator Ring @ ORNL.
2. Simulation: Use pyORBIT to simulate and cross-compare with experimental data for benchmarking, adding in the physical effects observed. Optimize via gradient descent algorithms to find best values for degrees of freedom in simulation we can't directly measure in experiment @ UChicago.

Experiment and Simulation Procedure

1. Injection: Inserting 1 ms train of 1 μs p^+ bunches. p^+ Energy (after linac) = 1.3 GeV; $\Delta E_{opt,BFGS}$= 0.001 GeV; Max. h=1 RF Voltage = 10 kV; 1000-1200 turns; Beam Width = 36.0/64.0; 100-300 Injection Turns → JOHO distribution in x-y plane, Gaussian distribution in z axis.
2. Tracking: Turn-by-turn tracking through SNS Ring lattice (includes beam position monitors, DRIFT, COL, OCT, Q, DH/DB, IKICK, vacuum control systems).
   - Longitudinal Space Charge: Self-induced $\vec{E}_{beam\ axis}$ caused by non-uniformities in the beam's line charge density – acts back on particles, causing bunch distortion, tune shift, instabilities.

$$E_z(r,z) = -\frac{Q}{2\pi\varepsilon_0\gamma^2}\Lambda\frac{d\lambda(z)}{dz}$$

   - RF Cavities: Apply time varying $\vec{E}$ creating a potential well (RF bucket).
3. Diagnostics: Beam Current Monitor (Amps).

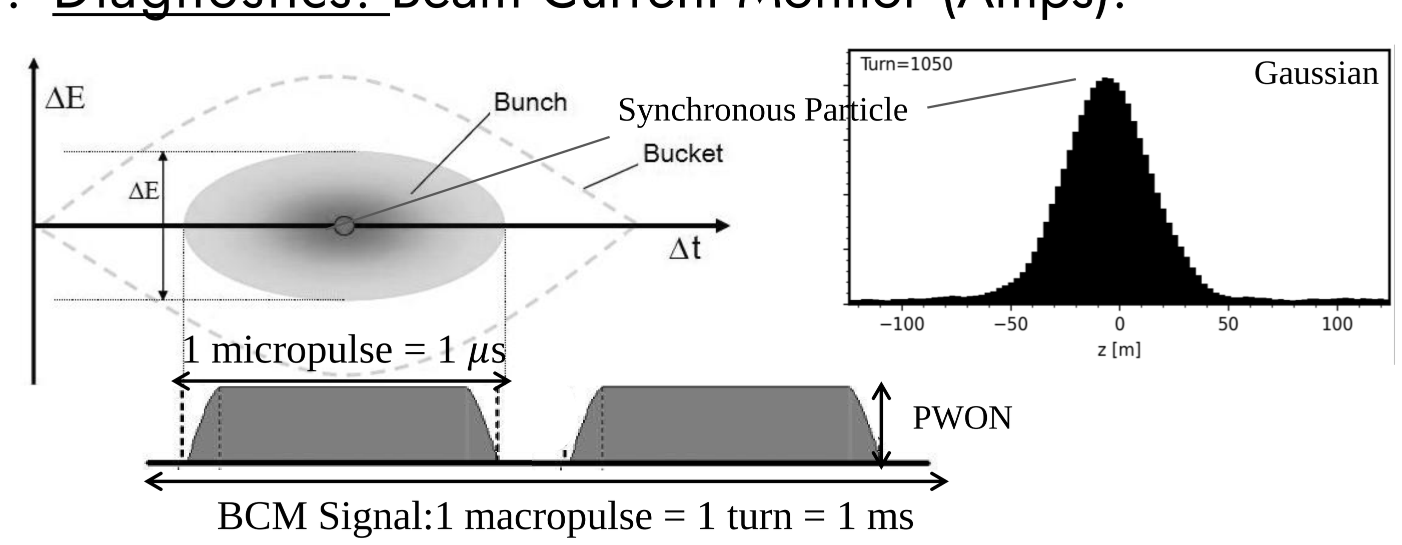


Figure 3: RF Cavity Operation: RF Bucket in phase space (left), longitudinal spread of the bunch within the bucket (right).

Results

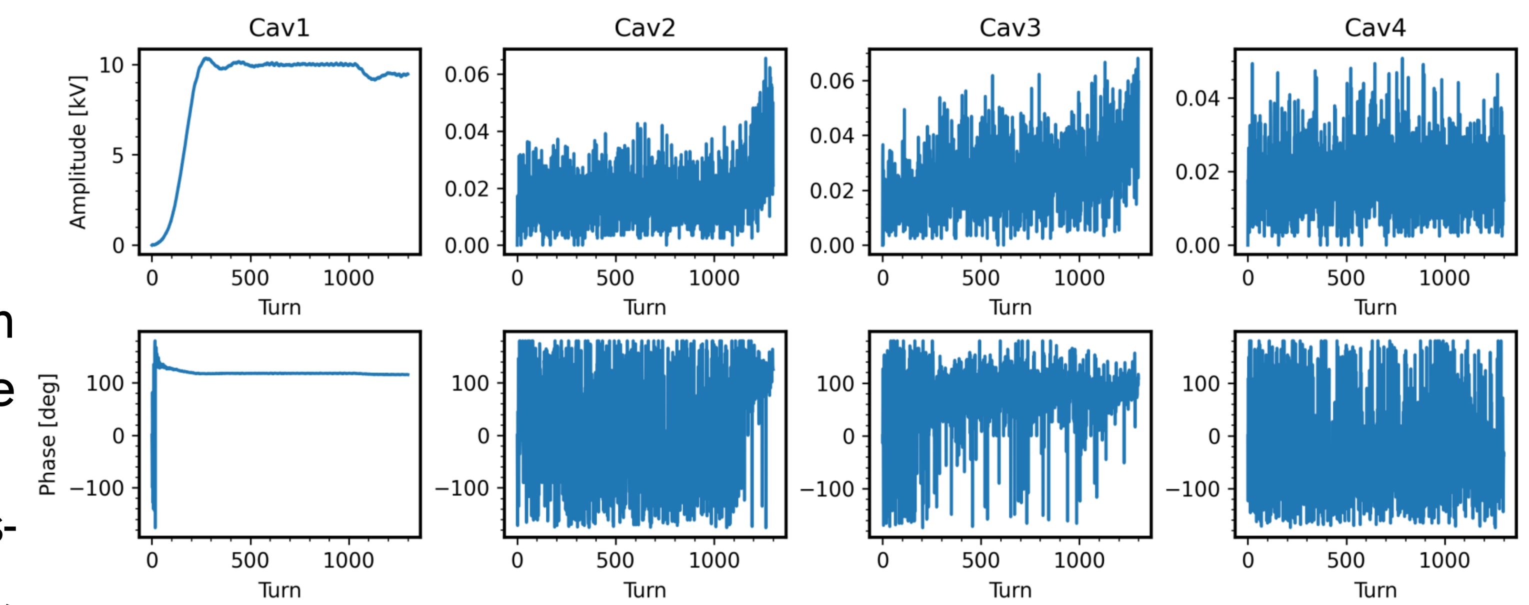


Figure 4: Experiment 02 Case 03 Low-Level RF Waveforms: RF Voltage v. Turn (top), RF Phase v. Turn (bottom) Turn for all 4 RF Cavities

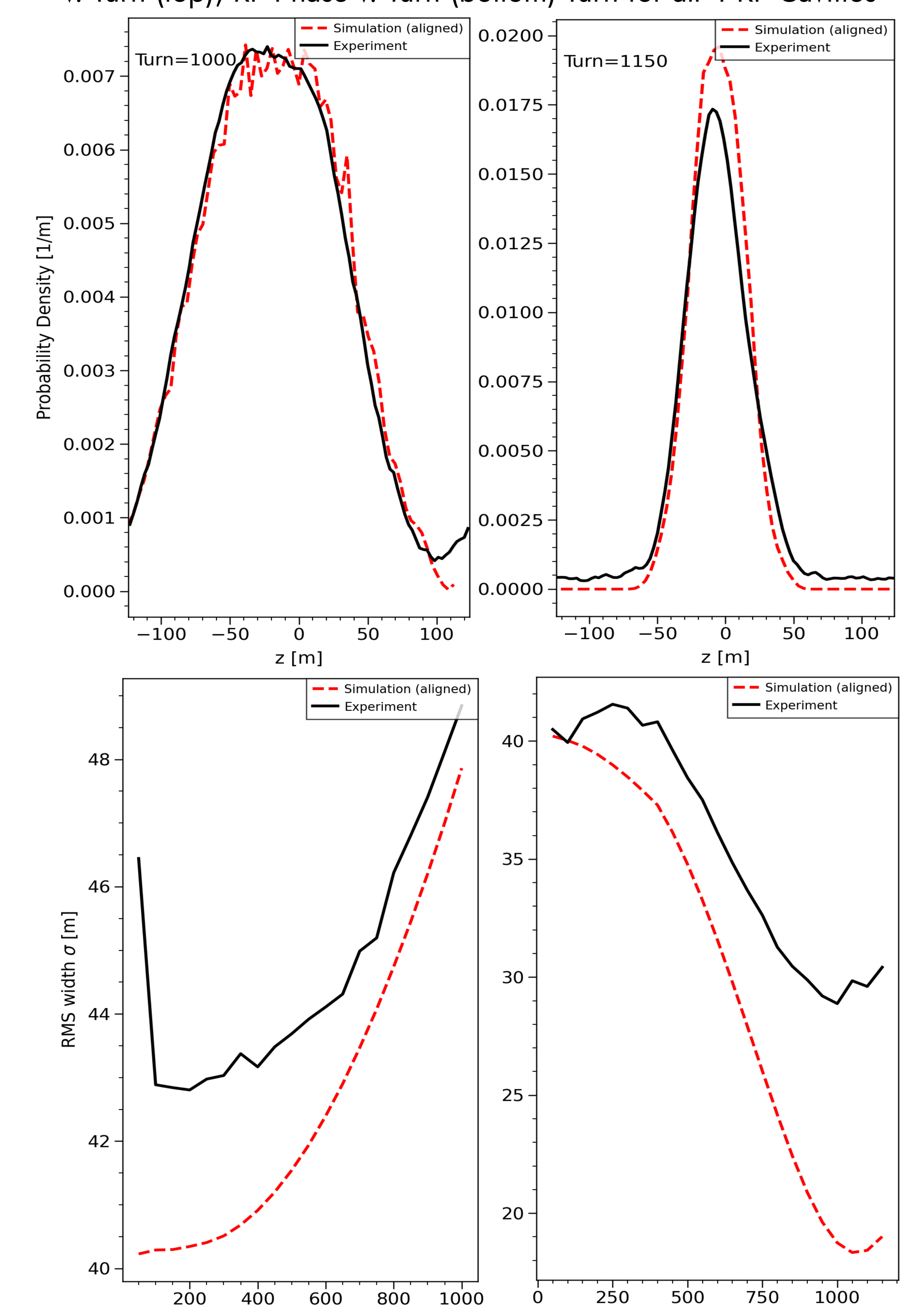


Figure 5: Simulation and Experimental Results for Experiment 01 (left) and Experiment 02 Case 03 (right) of longitudinal spread after turn 1000 (top) and RMS width v. Turns (bottom)

Experiment 02 C03 RMS width range: ~106 – 154 ns

Simulation 02 C03 RMS width range: ~66 – 146 ns

Conclusion & Extensions

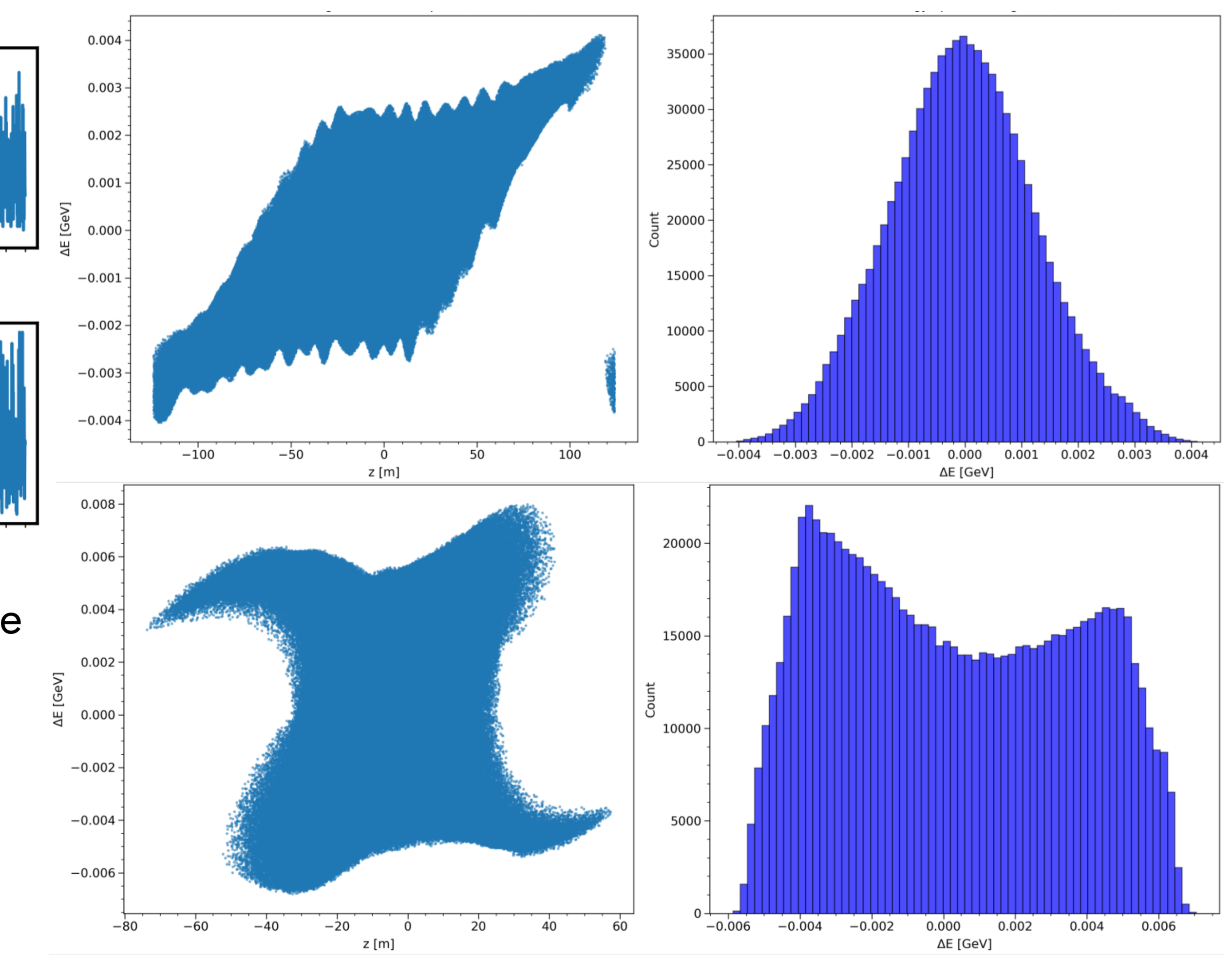


Figure 6: Simulation Phase Space Diagrams for Experiment 01 (top left) and Experiment 02 Case 03 (bottom left) with their respective ΔE histograms at turn 1000

1. Bunch compression stronger than that of baseline operations in the SNS ring was demonstrated, indicating the likelihood of being able to further compress the bunch for MuC studies using the ring, even before IMCC proposed hardware updates such as adding another ring.
2. It was shown there are limitations in the physical effects accounted for in pyORBIT that need to be addressed. This includes numerical instabilities in 1D space-charge (3D needed) as well as a model of the RF system that takes beam loading into account, higher complexity beam-cavity interactions.
3. Further experiments changing the timing, relative phase difference, feedback, and voltage of RF cavities as well as number of injection turns were conducted.

References

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