

Designing experiments to study beam dynamics at high space charge intensities in the SNS AR

Austin Hoover

7th ICFA Workshop on Space Charge | Oxford, UK

September 30, 2026

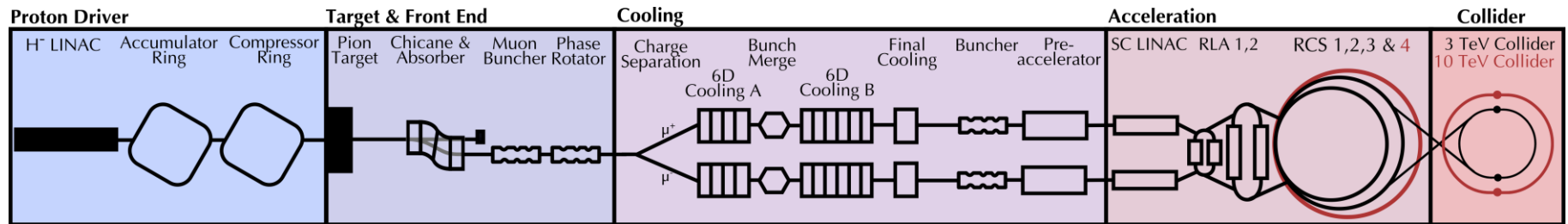


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Space charge will play an important role in next-generation hadron accelerators

- Muon Collider (MuC) would require strong bunch compression after accumulation.
- Compression will create extreme space charge forces (albeit for a short time).
- High power = strict loss requirements ($< 1 \text{ W/m}$)

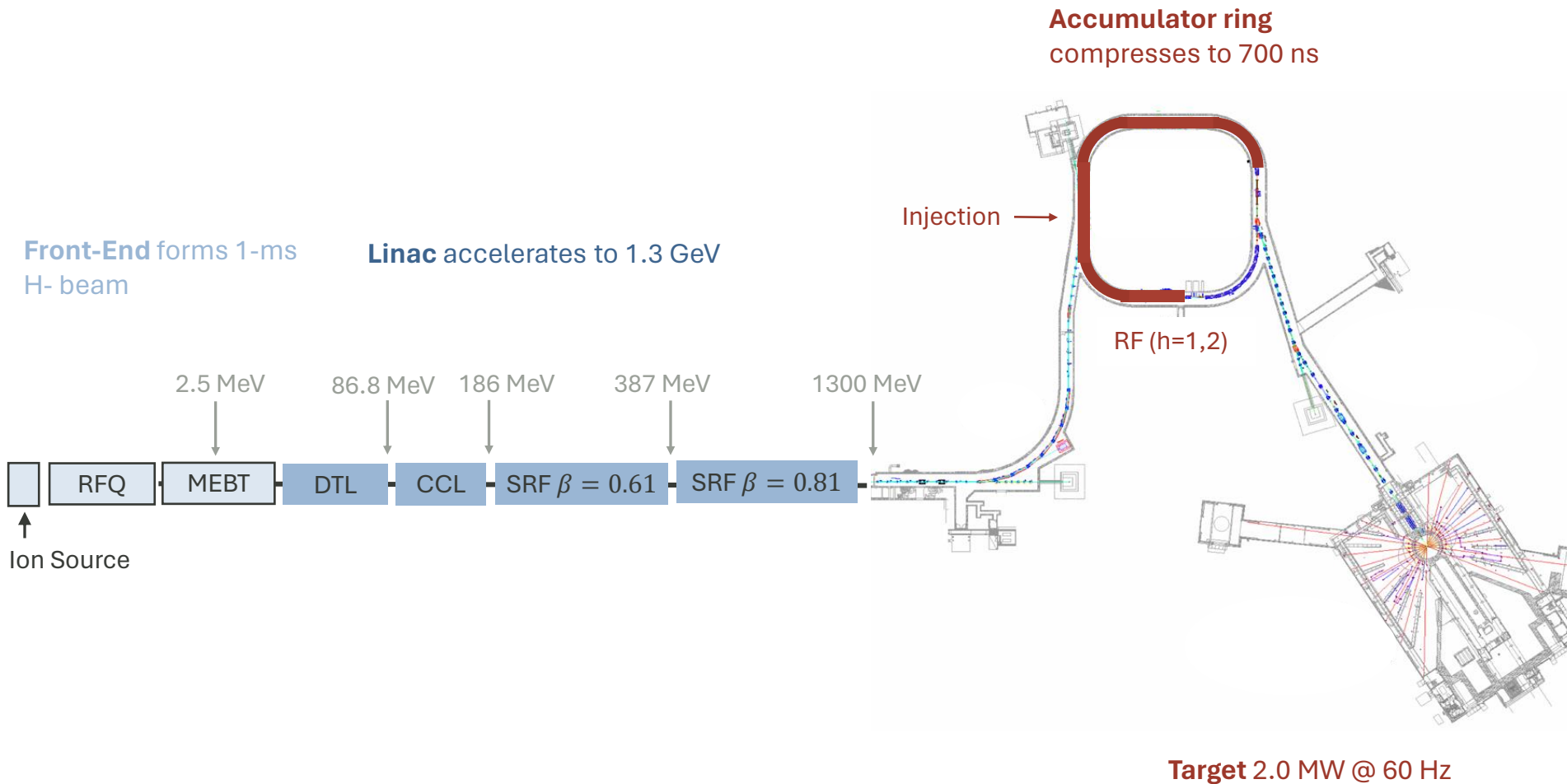


↑
2-4 MW, 5-10 Hz, 1-3 ns

Some model predictions have not been directly observed in experiment

“Advances made over the past few years have helped to arrive at a more balanced understanding of these mechanisms and narrow the gap between highly idealized analytical models and multi-particle simulations—a trend that is encouraging and should be promoted. It cannot be overlooked, however, that **systematic and clear experimental data on space charge physics processes is difficult to obtain in production accelerators and therefore still quite limited**. This is to a large extent due to the challenges of having **sufficient diagnostics** and getting enough **access to beam time** on devices that are primarily user facilities. The impression of many workers in the field [that the **gap between theory—including simulation—and the real world** of operating accelerators is still considerable] is not misleading.”
\cite{hofmann_space_2017}

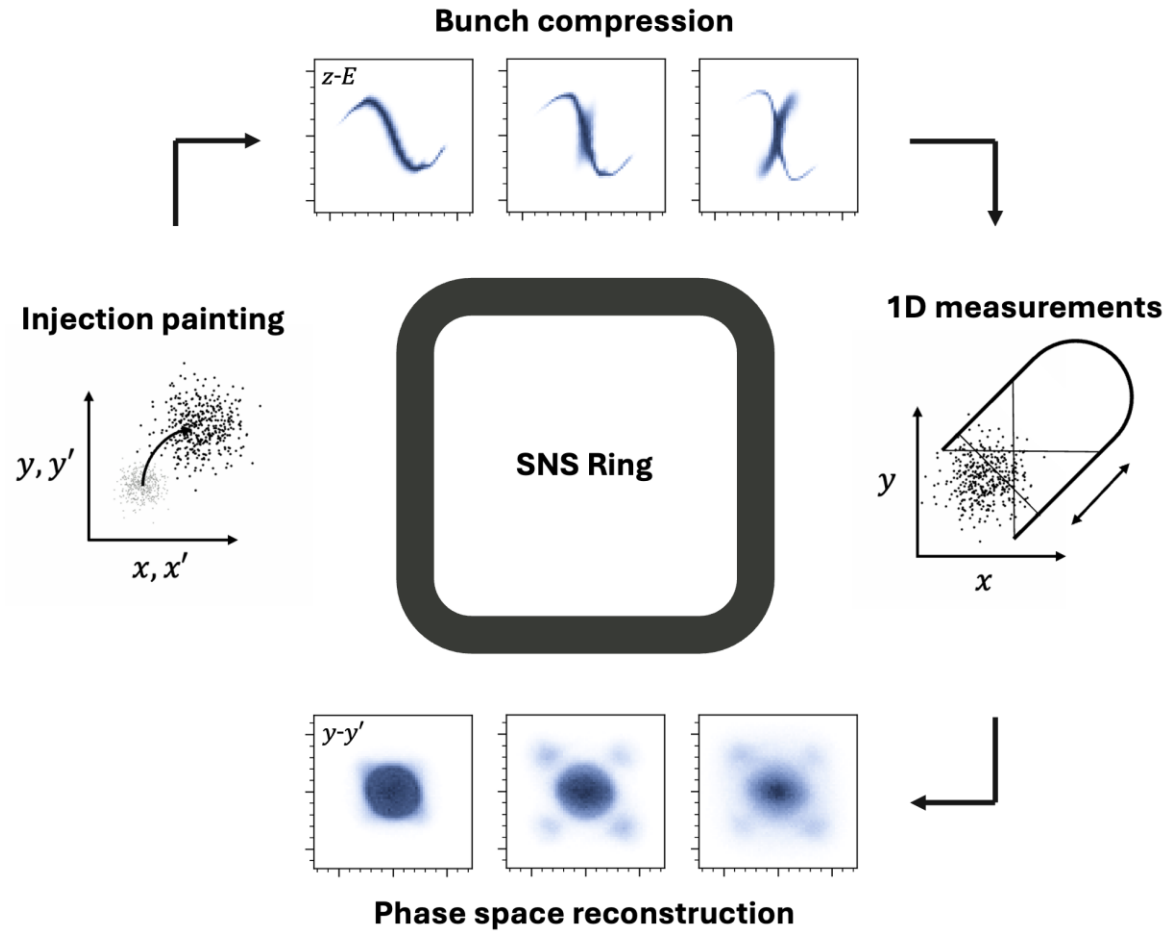
Experiments at SNS could provide valuable data



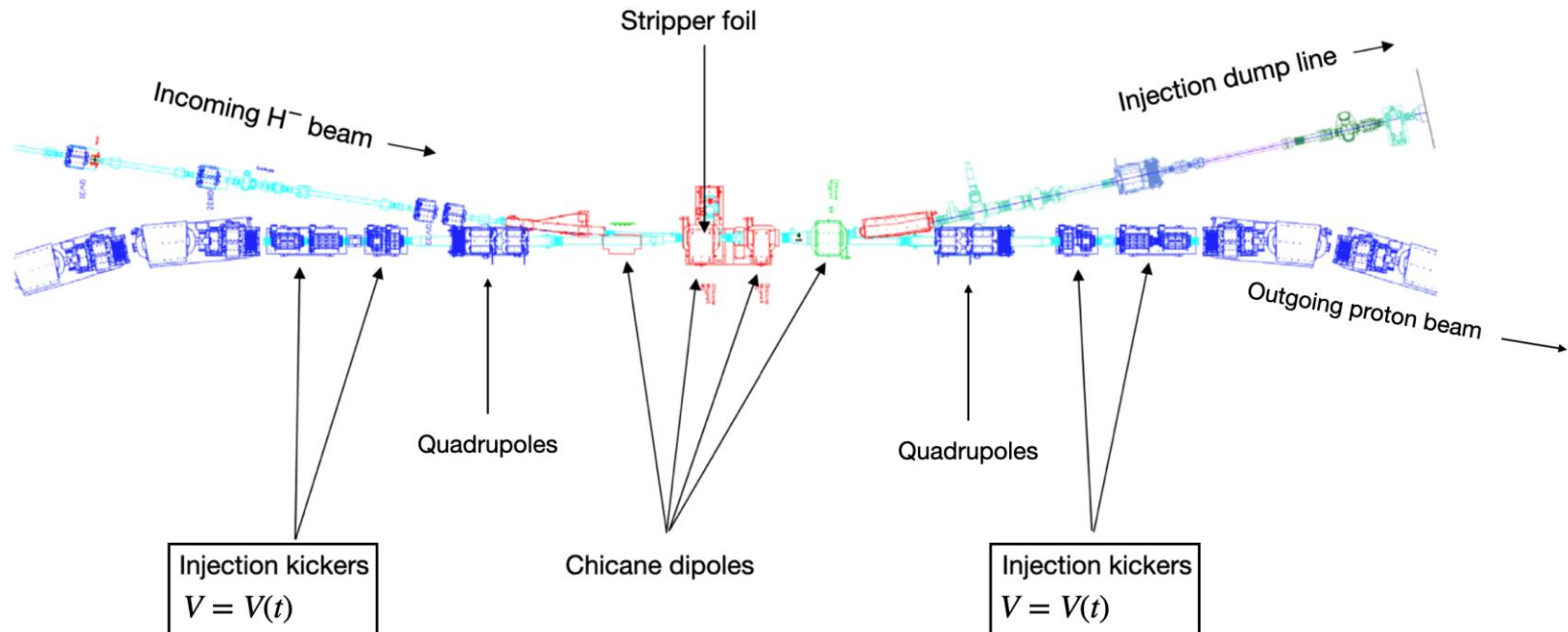
Experiments at SNS could provide valuable data

- Largest single-bunch intensity (2.25×10^{14} / 2.8 MW-equivalent)
- Flexible energy range (1.3 $\rightarrow$ 0.8 GeV, gamma ratio 1.3, perveance ratio 2.5)
- Beam shaping (painting + compression)
- Detailed transverse diagnostics (MENT, e-scanner)

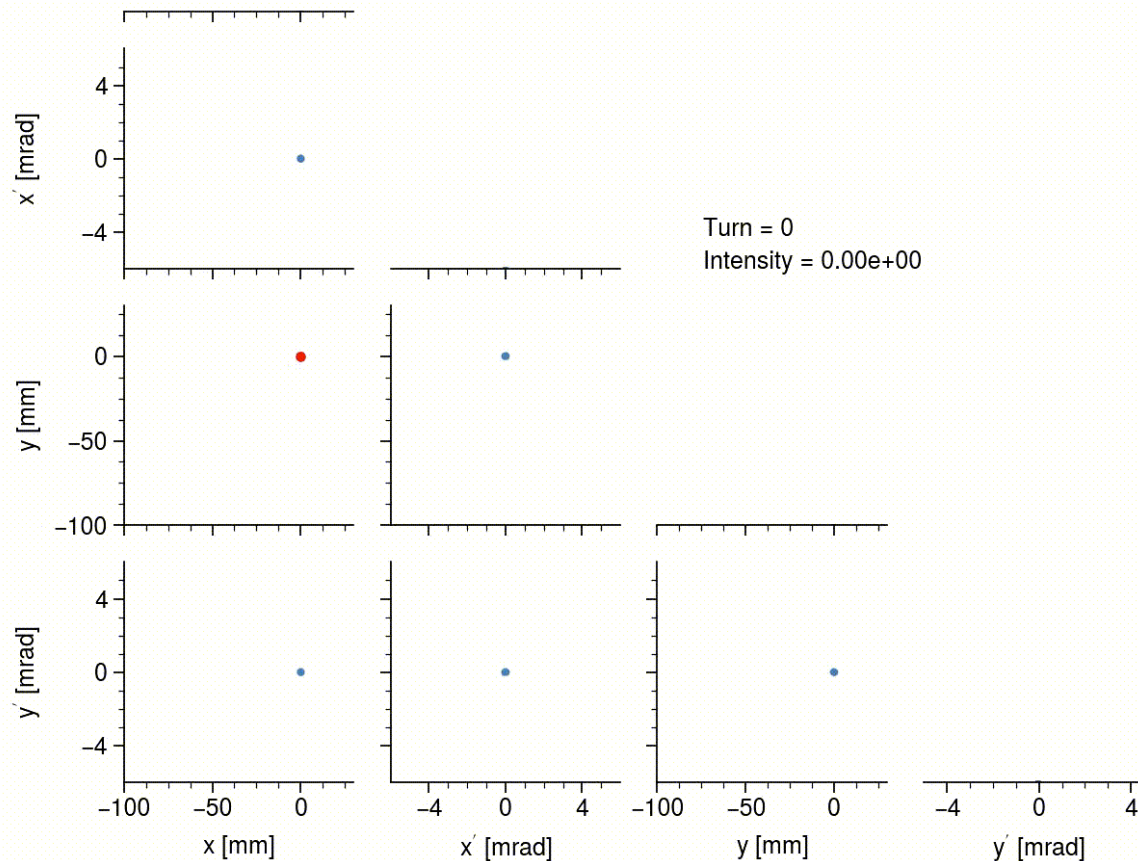
Summary of proposed research



Painting waveforms could be modified to launch variety of initial distributions



Painting waveforms could be modified to launch variety of initial distributions

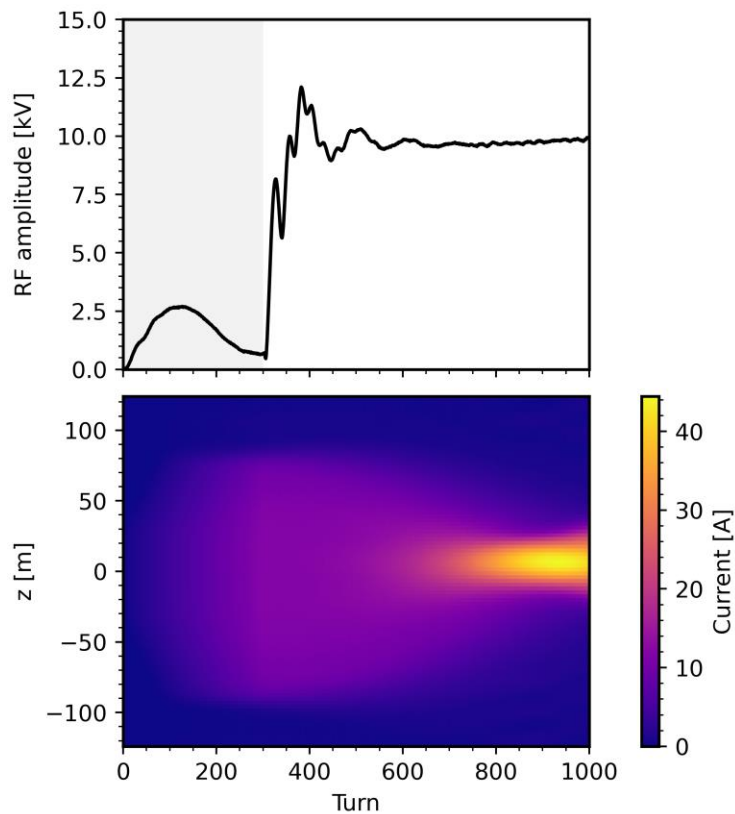


Bunch compression experiments have begun using existing hardware/software

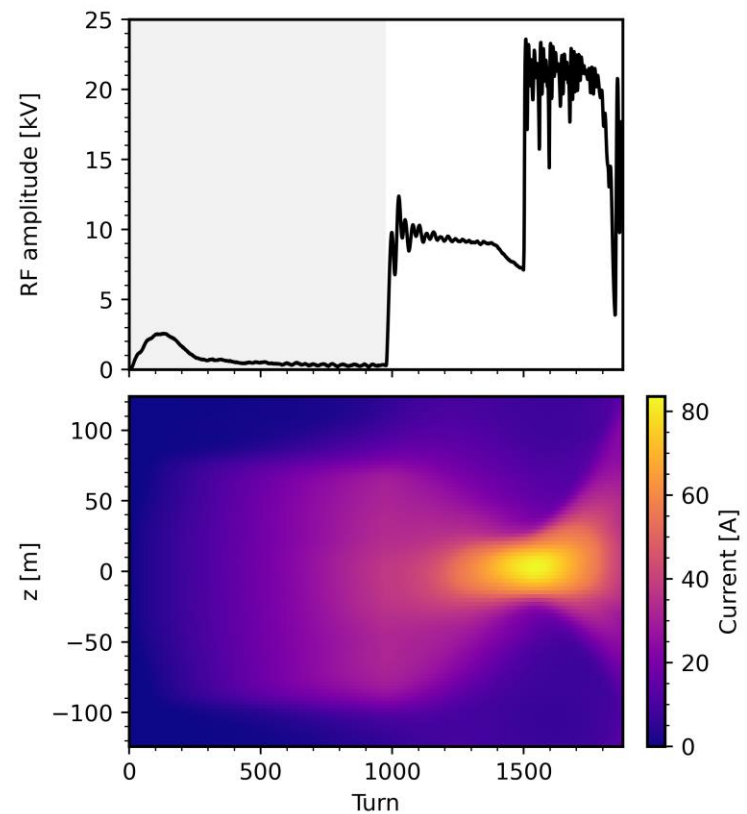
- SNS has four RF cavities ($h=1$, $h=1$, $h=2$, $h=2$)
- Each cavity can run at either harmonic.
- Each cavity has operating limit of 10 kV. 18 kV tests (no beam) were performed during SNS commissioning.
- Need to find optimal combination of voltage, phase, feedback, feedforward to maximize compression ratio + troubleshoot RF issues.

Initial experiments demonstrated 2.5x increase in peak density for 1.9 MW-equivalent beam

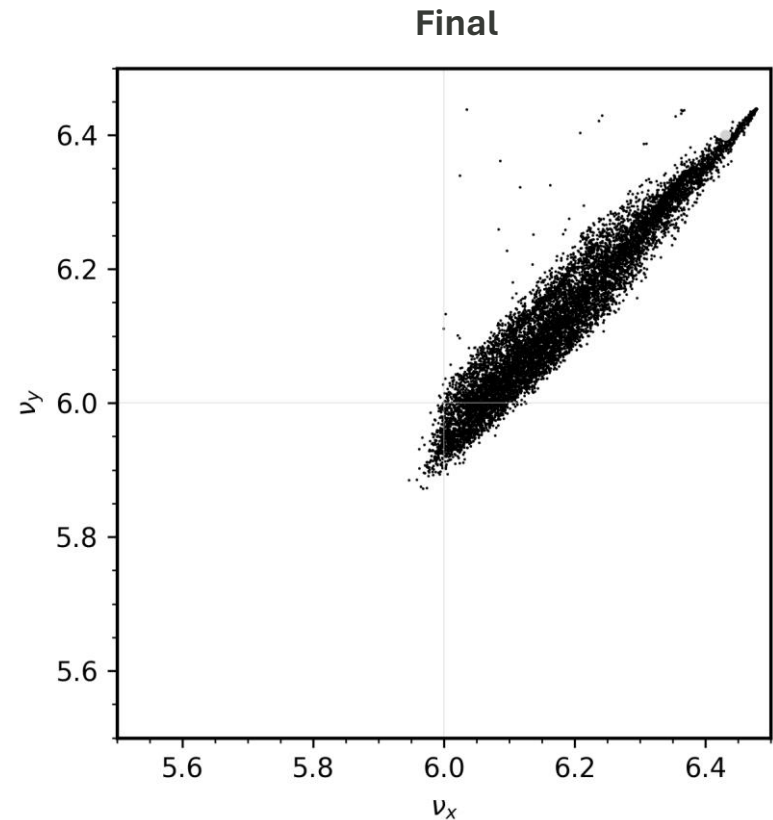
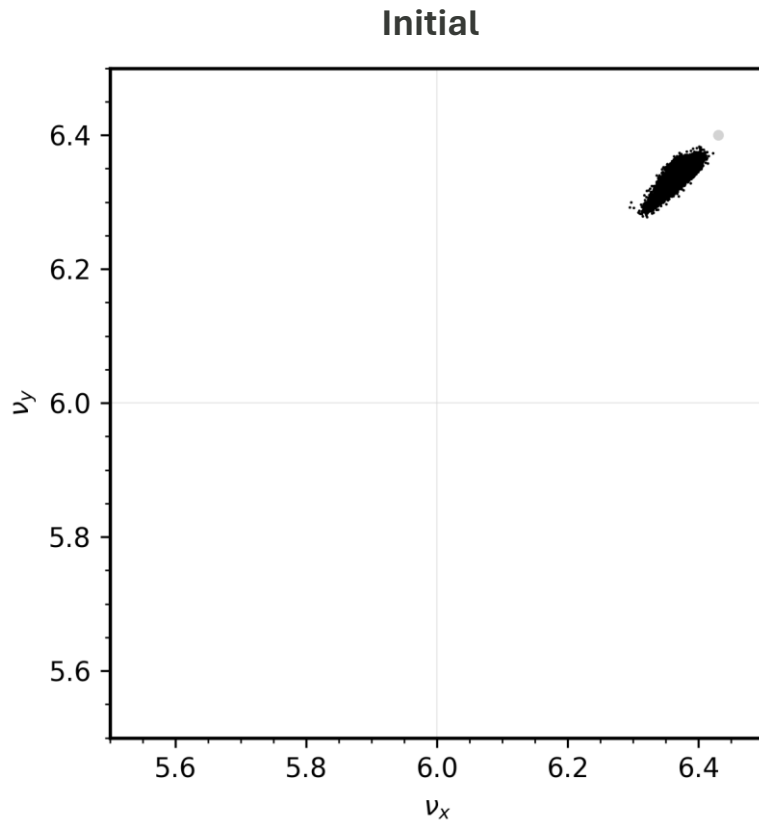
300-turn injection



1000-turn injection

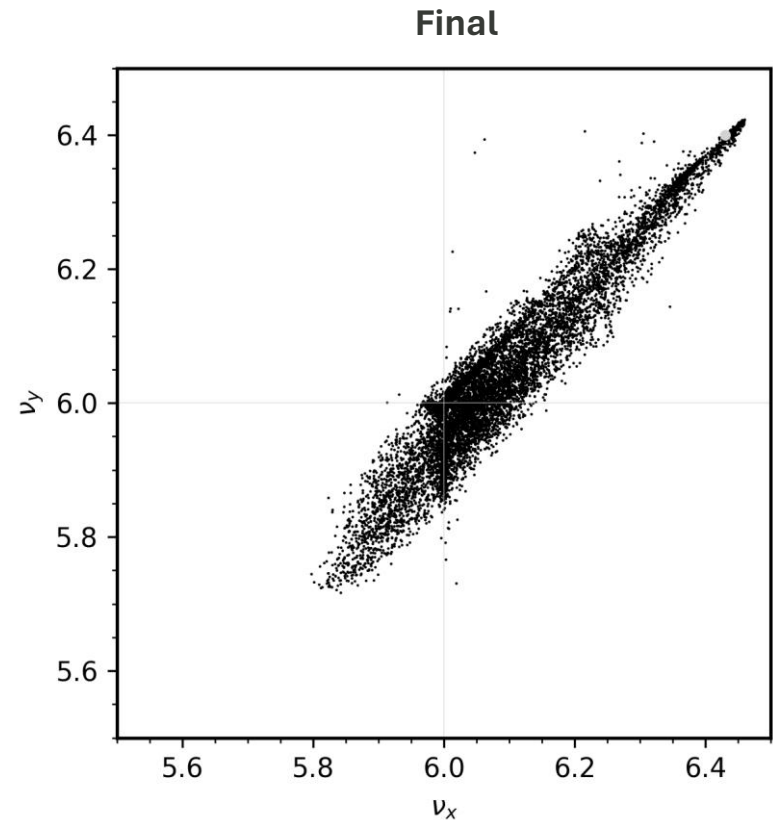
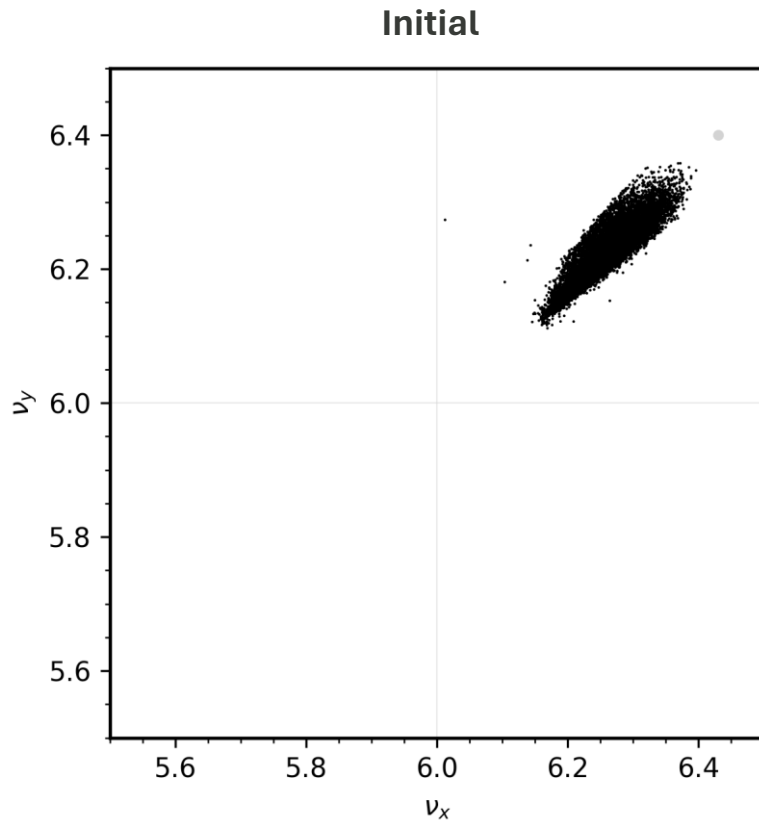


Large tune shifts/spreads possible with moderate compression ratios



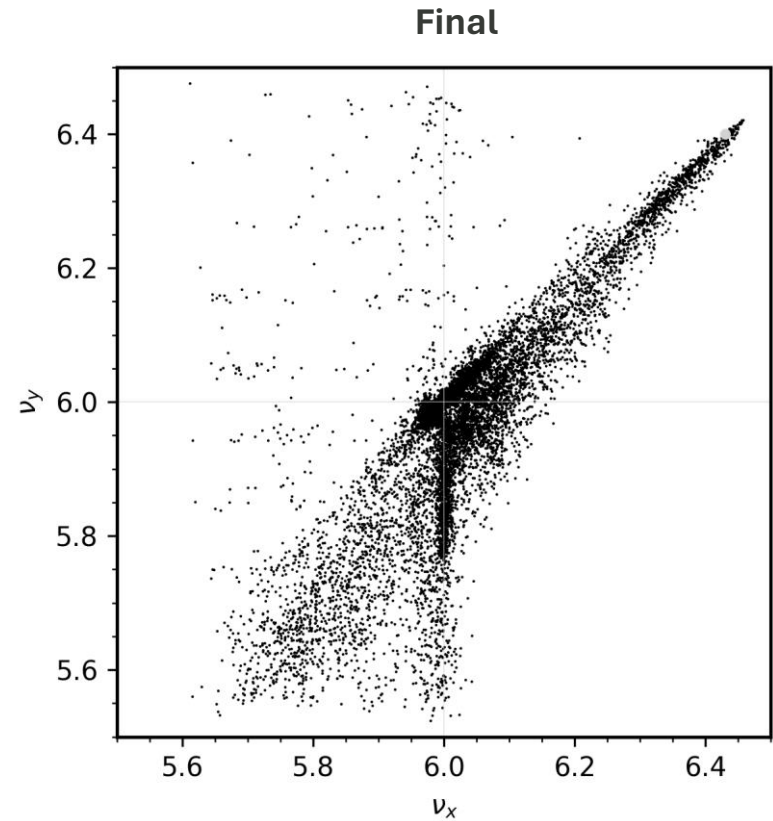
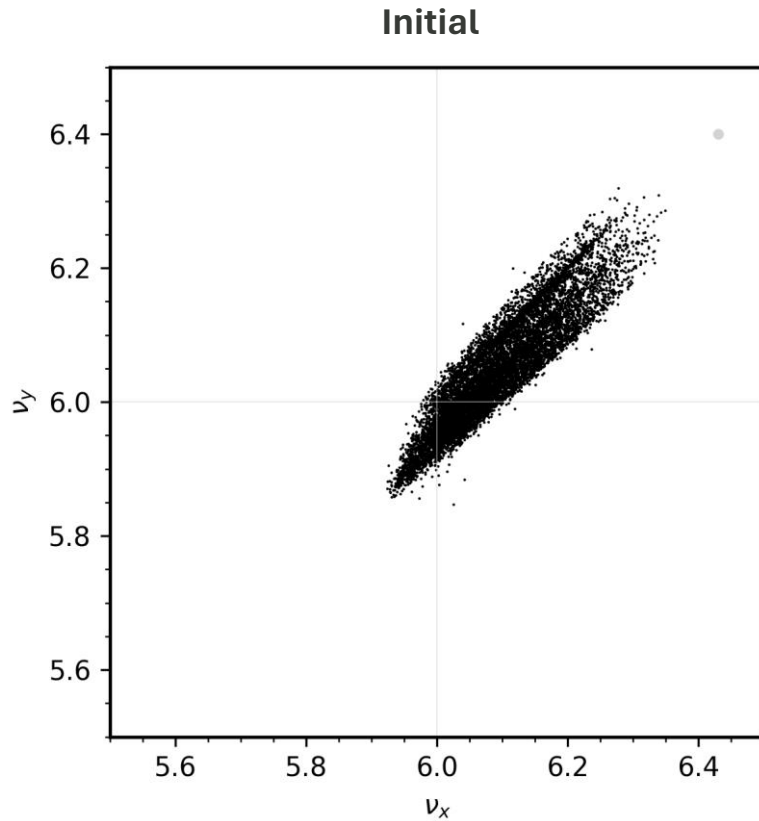
Gaussian, 1.3 GeV, 25 mm mrad

Large tune shifts/spreads possible with moderate compression ratios



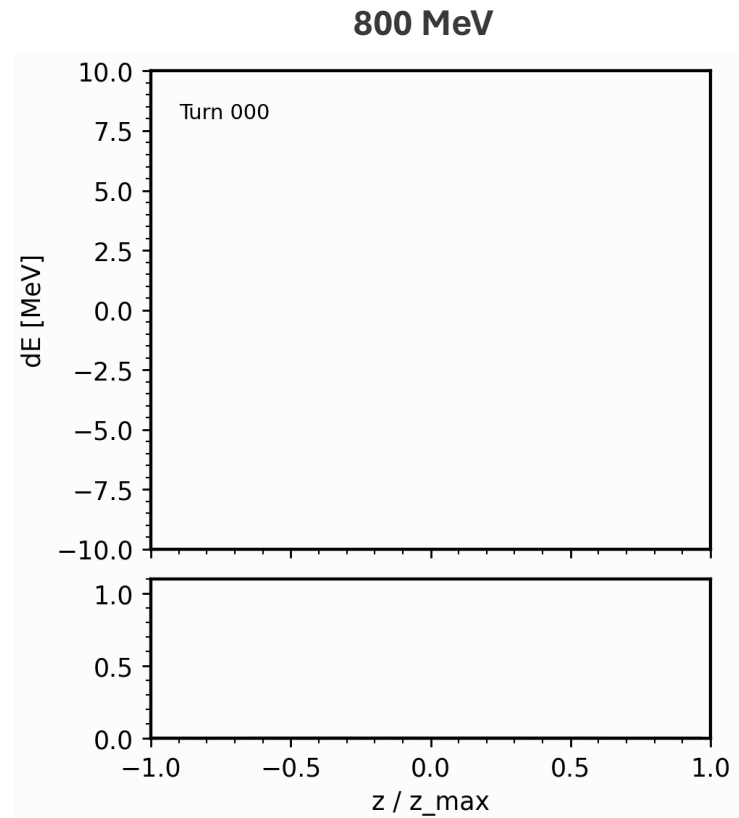
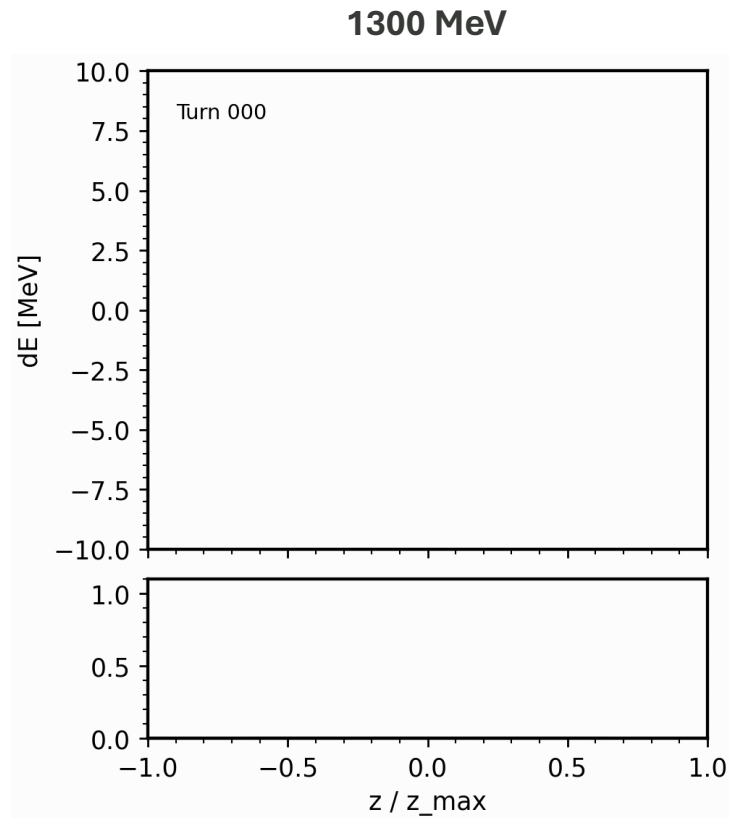
Gaussian, 0.8 GeV, 25 mm mrad

Large tune shifts/spreads possible with moderate compression ratios

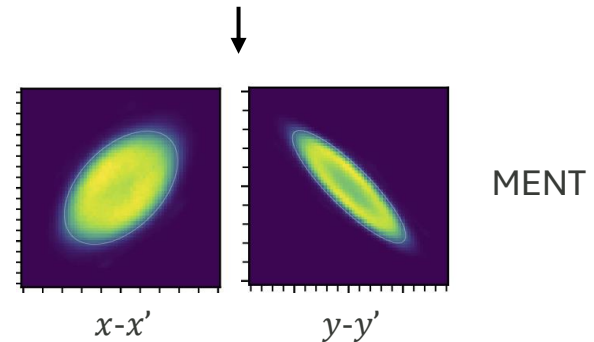
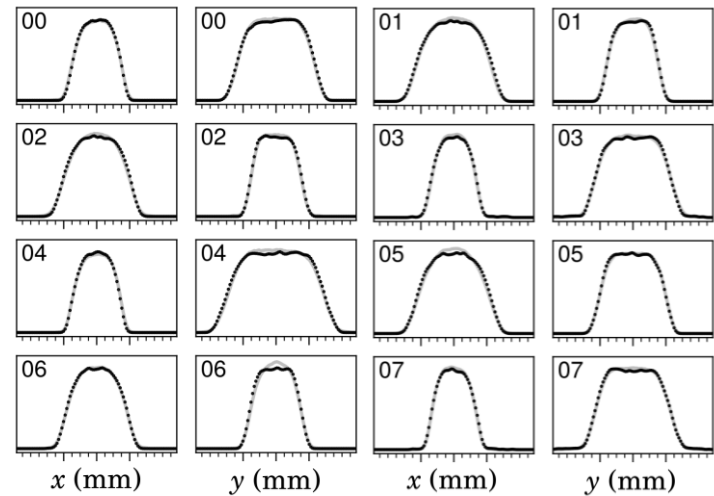
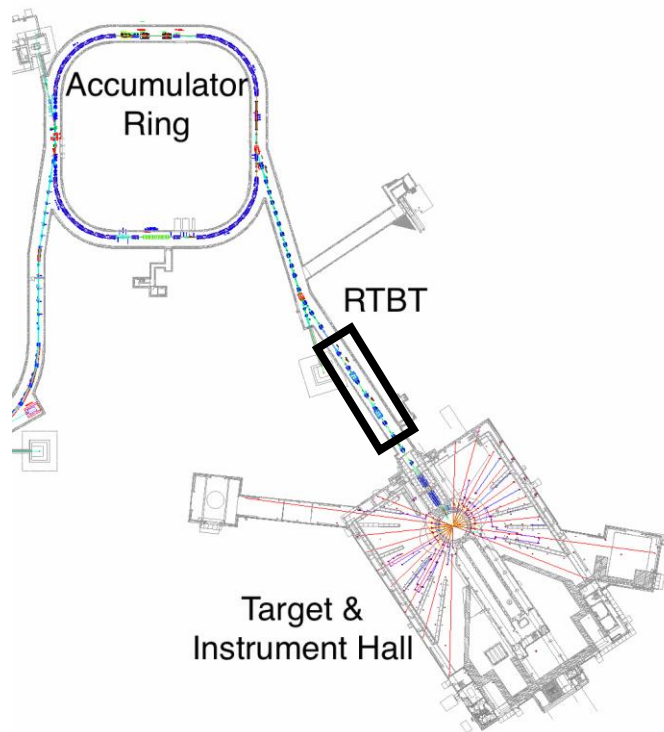


Gaussian, 0.8 GeV, 12 mm mrad

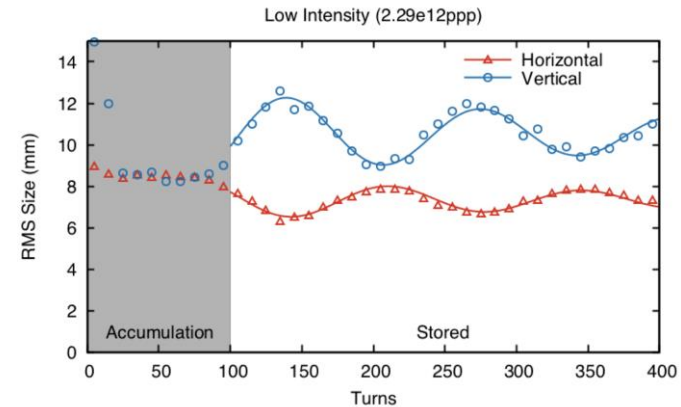
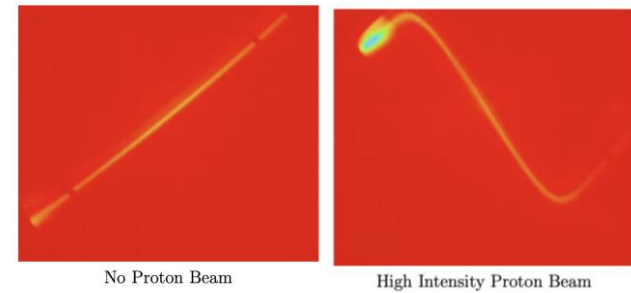
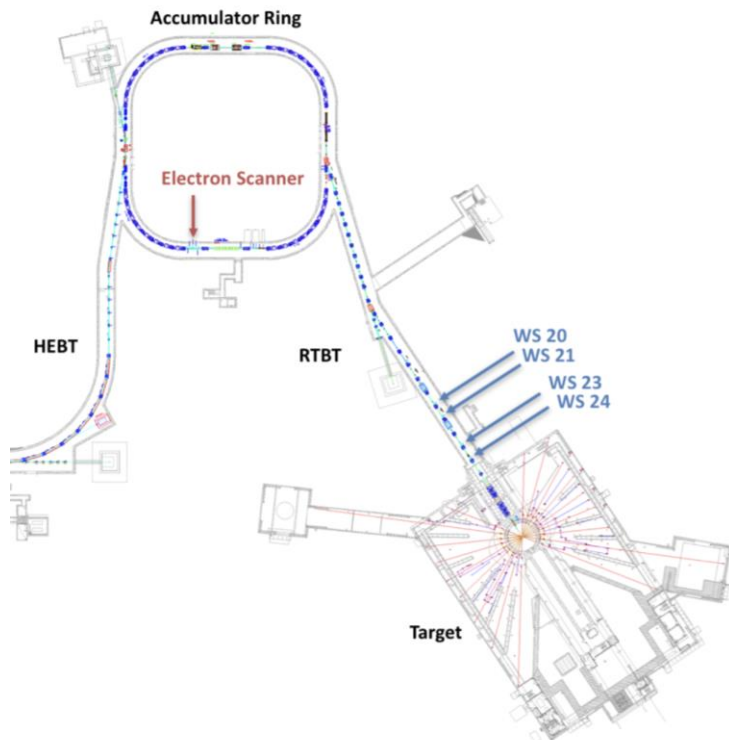
Longitudinal space charge expected to influence compression



Wire scanners constrain phase space distribution of accumulated beam (2D/4D)

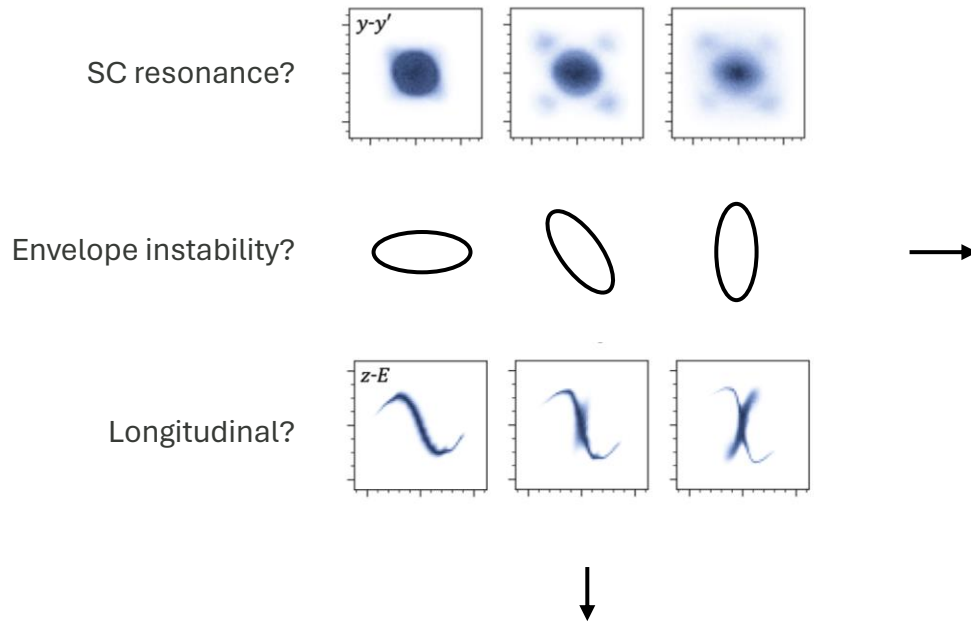


Electron scanner will provide turn-by-turn profiles



Source: R. Potts, "Exploration of Equal Tune Transverse Coupling in the Spallation Neutron Source Accumulator Ring." (2017).

What could we measure?

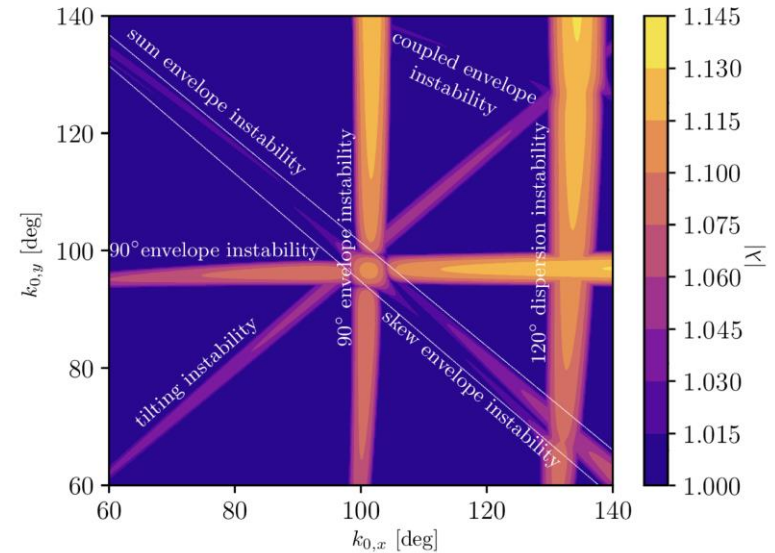


SPACE-CHARGE EFFECTS ON BUNCH ROTATION

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Intensity limitations due to space charge for bunch compression in synchrotrons

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²GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany

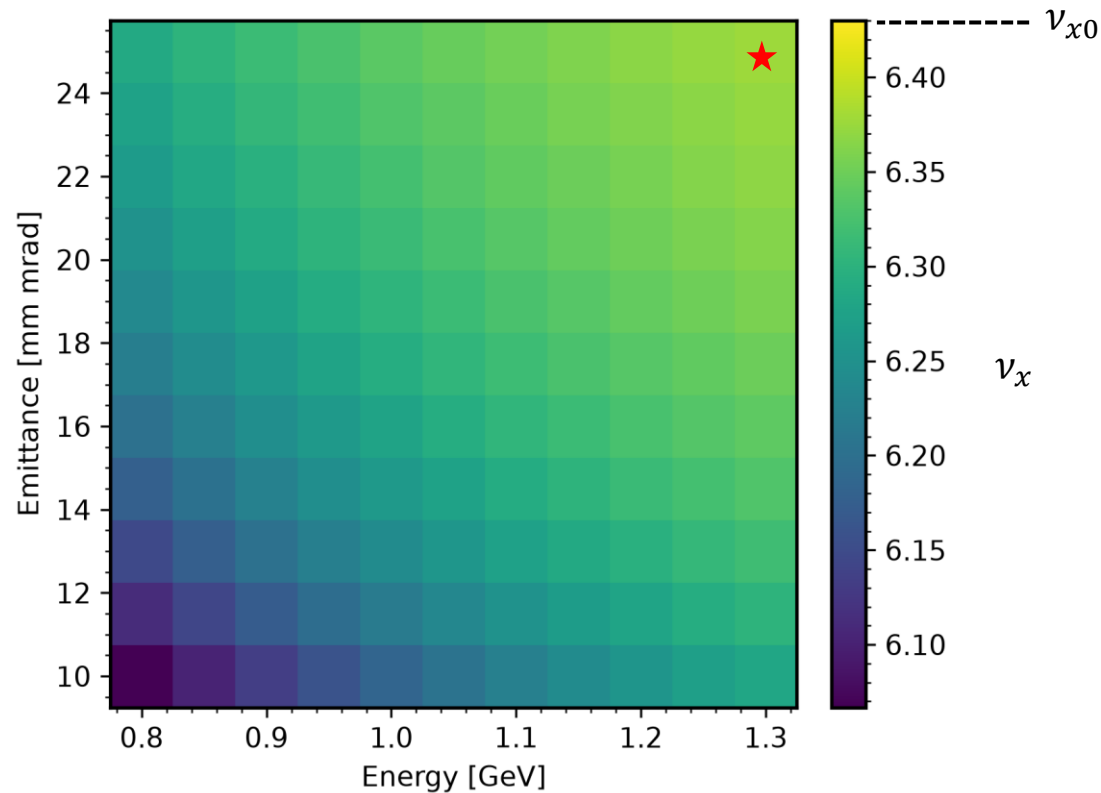
(Received 20 March 2018; published 9 July 2018)

Conclusion

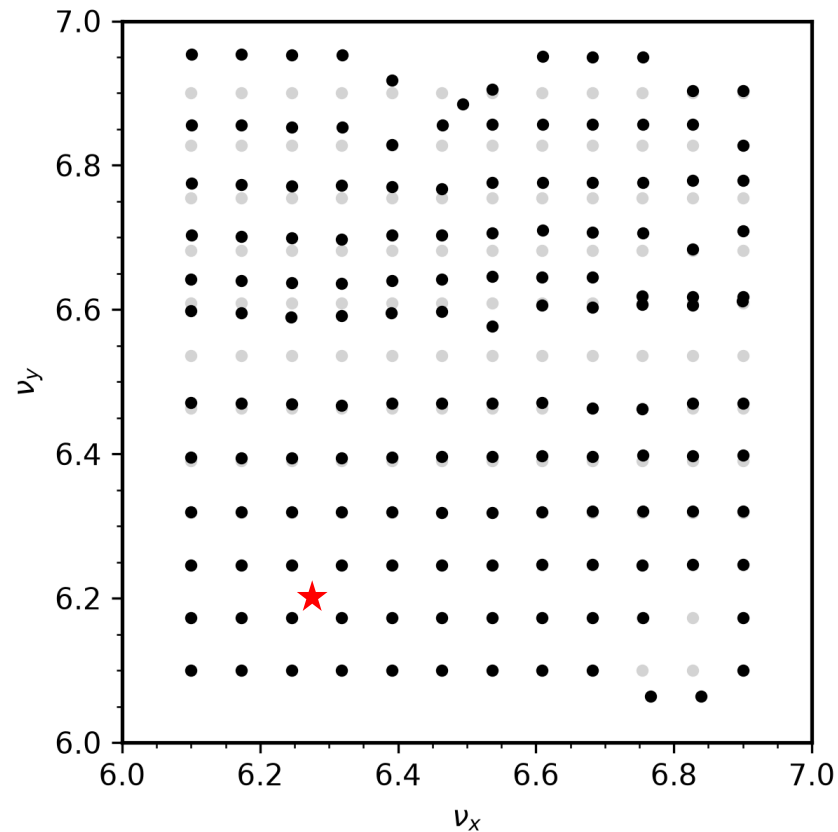
- Proposal: leverage SNS lattice flexibility + painting + compression + diagnostics to generate high-quality benchmarks of space charge effects in rings.
- Experiments could be relevant to next-generation facilities like MuC.
- Thanks for listening!

Extra slides

At reduced beam energy and painted emittance, KV tune shift approaches 0.4



MAD-X model can access most tunes in the range [6, 7]



1999-2002: papers studied behavior of KV distribution in newly designed SNS AR

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 2, 114202 (1999)

Space charge dynamics in high intensity rings

J. A. Holmes, V. V. Danilov, J. D. Galambos, D. Jeon, and D. K. Olsen
SNS Project, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-8218
(Received 9 July 1999; published 29 November 1999)

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It is therefore
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driven lattice
its dependence

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 4, 084202 (2001)

Instabilities of high-order beam modes driven by space-charge coupling resonances

A. V. Fedotov, J. A. Holmes, and R. L. Gluckstern
CA Department, Brookhaven National Laboratory, Upton, New York 11973,
SNS Project, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831,

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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 5, 024202 (2002)

Half-integer resonance crossing in high-intensity rings

A. V. Fedotov¹ and I. Hofmann²

¹*CA Department, Brookhaven National Laboratory, Upton, New York 11973*

²*GSI Darmstadt, Planckstrasse 1, 64291 Darmstadt, Germany*

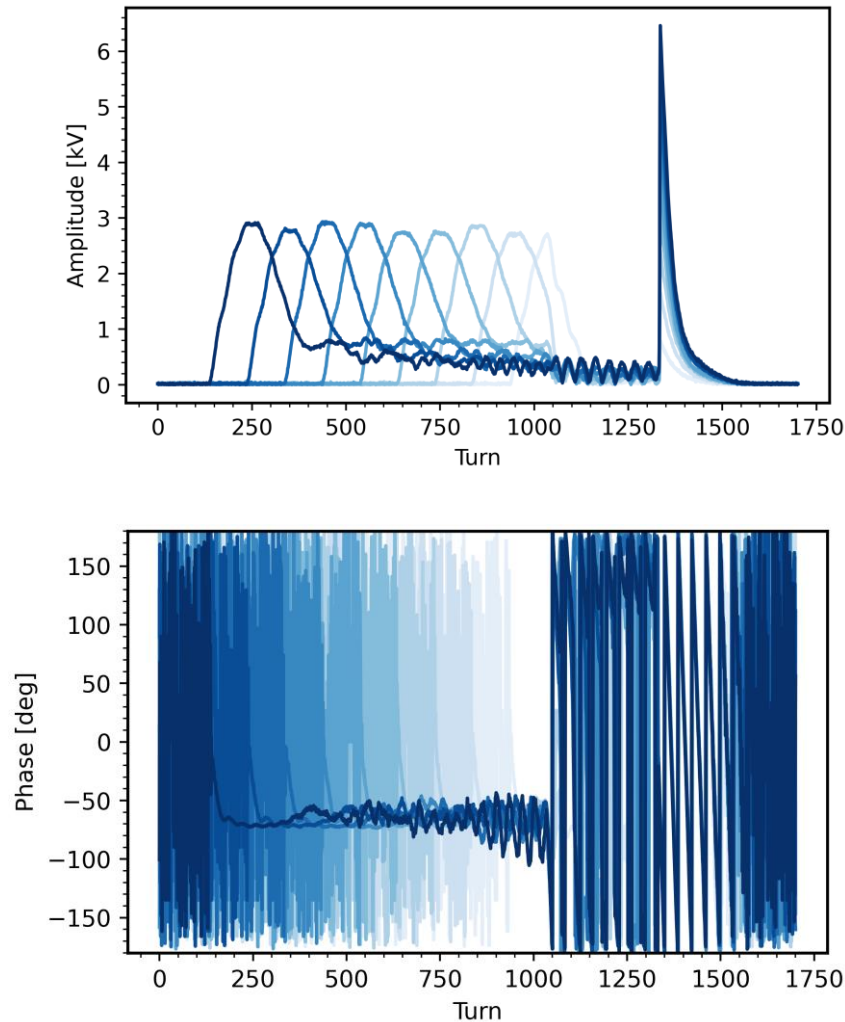
(Received 26 September 2001; published 25 February 2002)

A detailed study of the influence of space charge on the crossing of second-order resonances is presented and associated with the space-charge limit of high-intensity rings. Two-dimensional simulation studies are compared with envelope models, which agree in the finding of an increased intensity limit due to the coherent frequency shift. This result is also found for realistic bunched beams with multiturn injection painting. Characteristic features such as the influence of tune splitting, structure resonances, and the role of envelope instabilities are discussed in detail. The theoretical limits are found to be in good agreement with the performance of high-intensity proton machines.

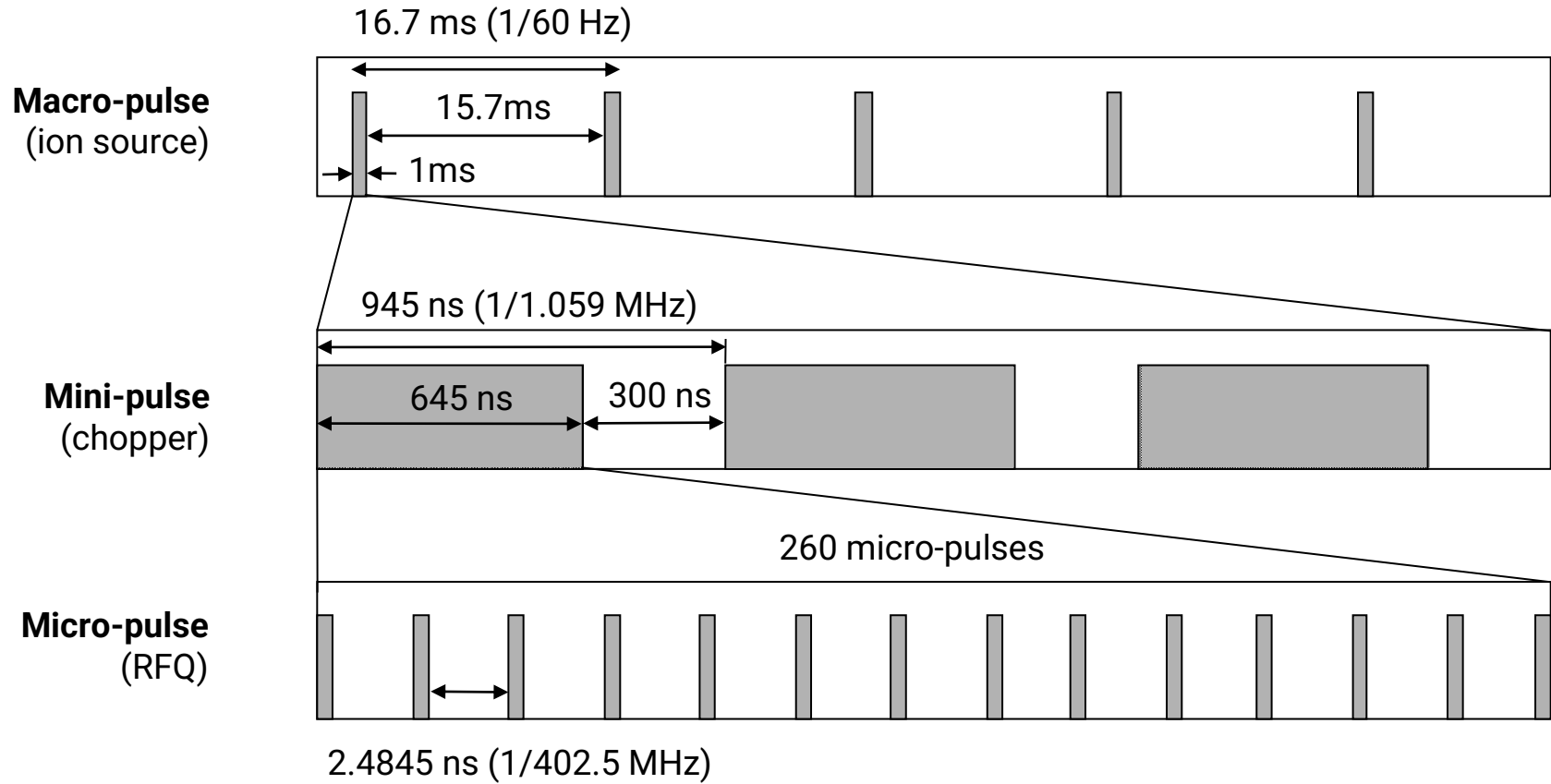
DOI: 10.1103/PhysRevSTAB.5.024202

PACS numbers: 29.27.Bd

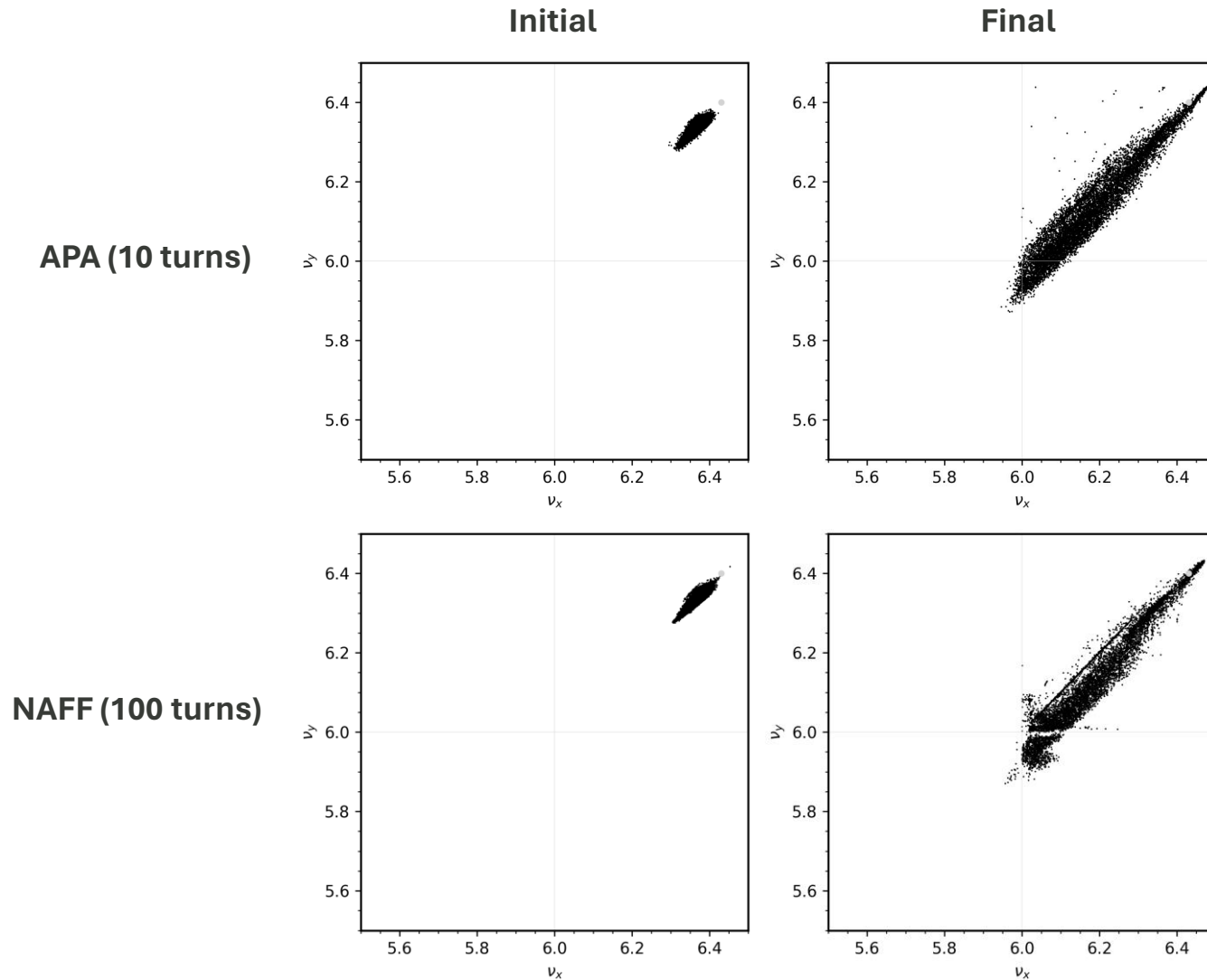
RF feedback loop can eventually offset most beam-induced voltage



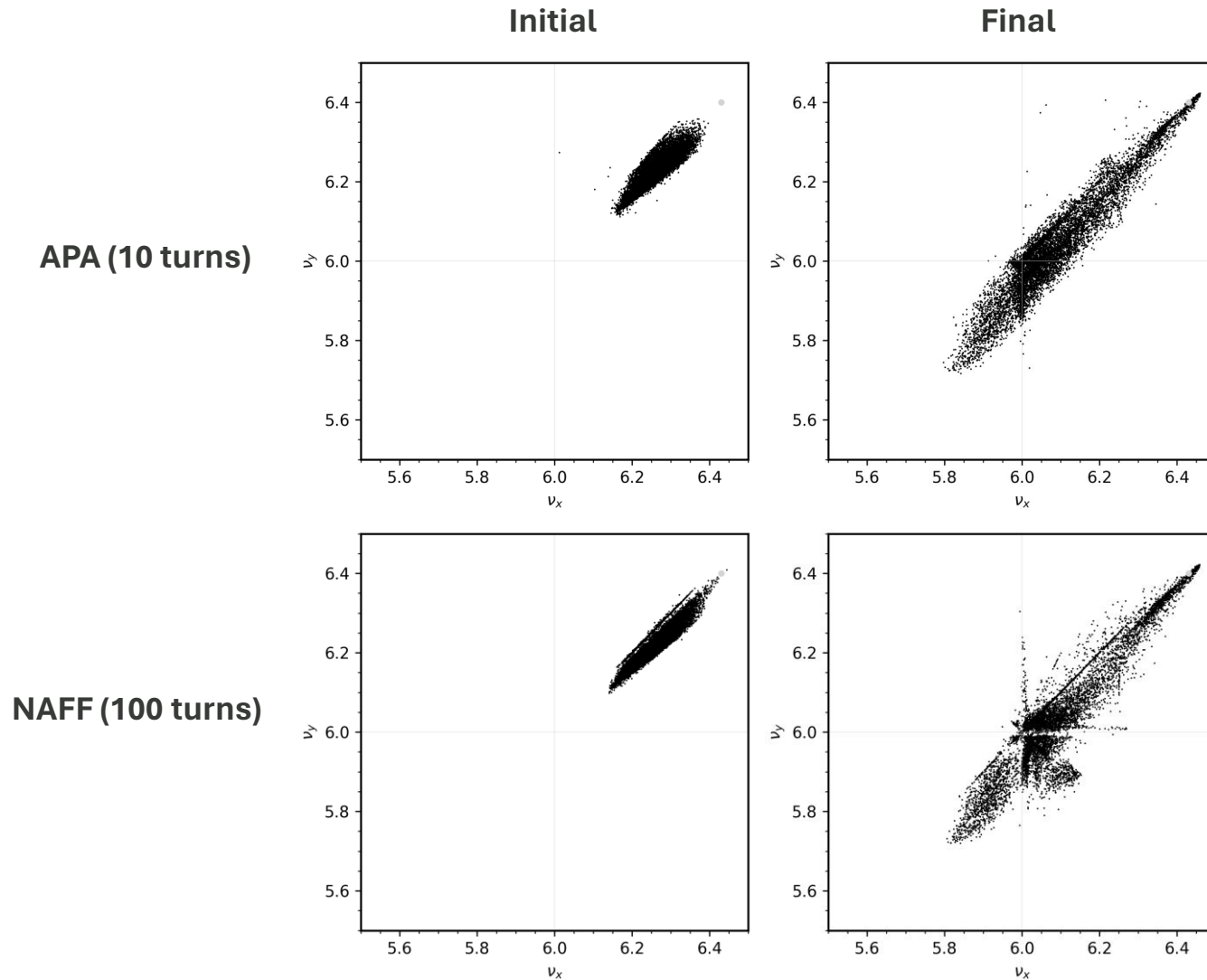
SNS pulse structure



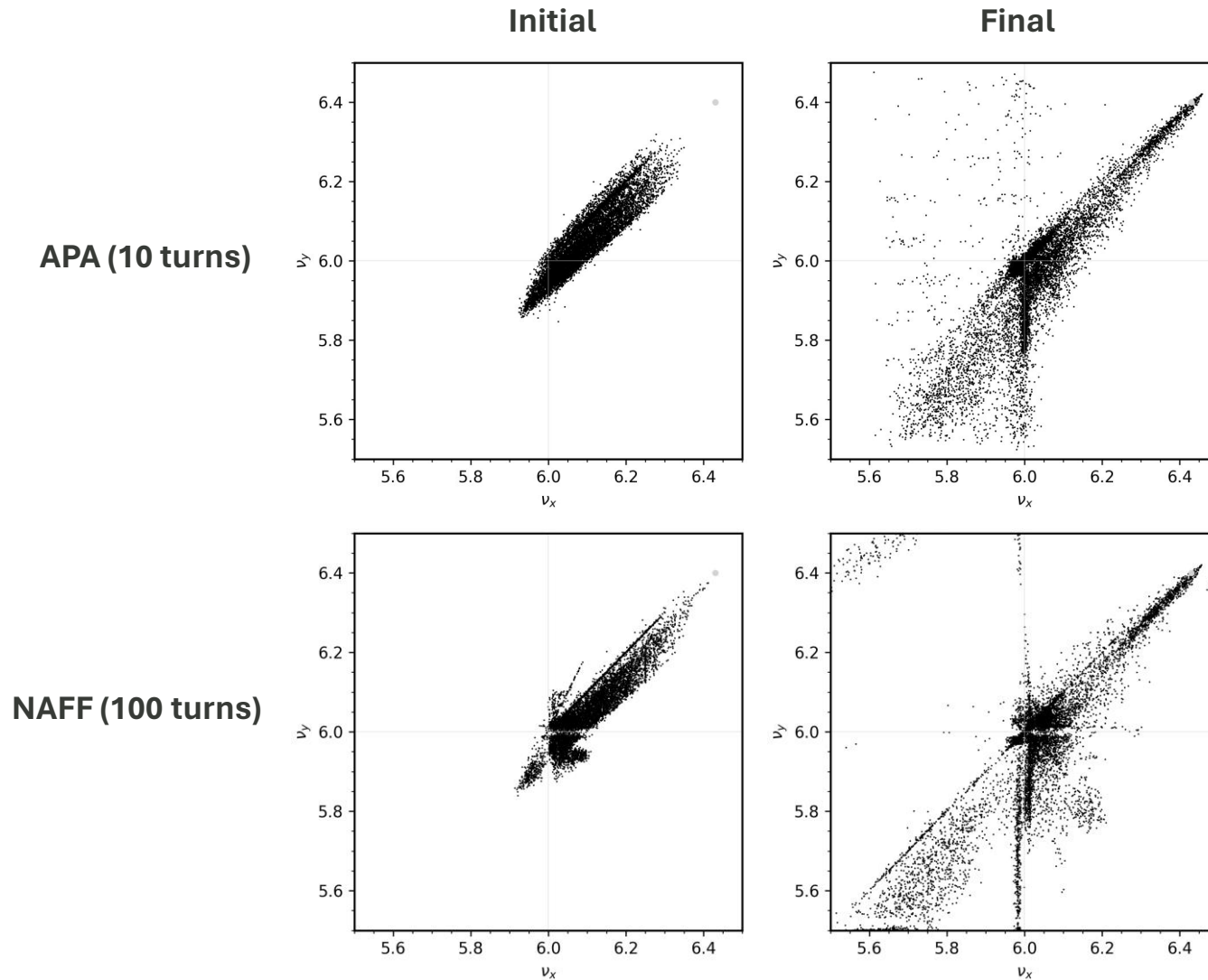
APA vs. NAFF tunes during compression



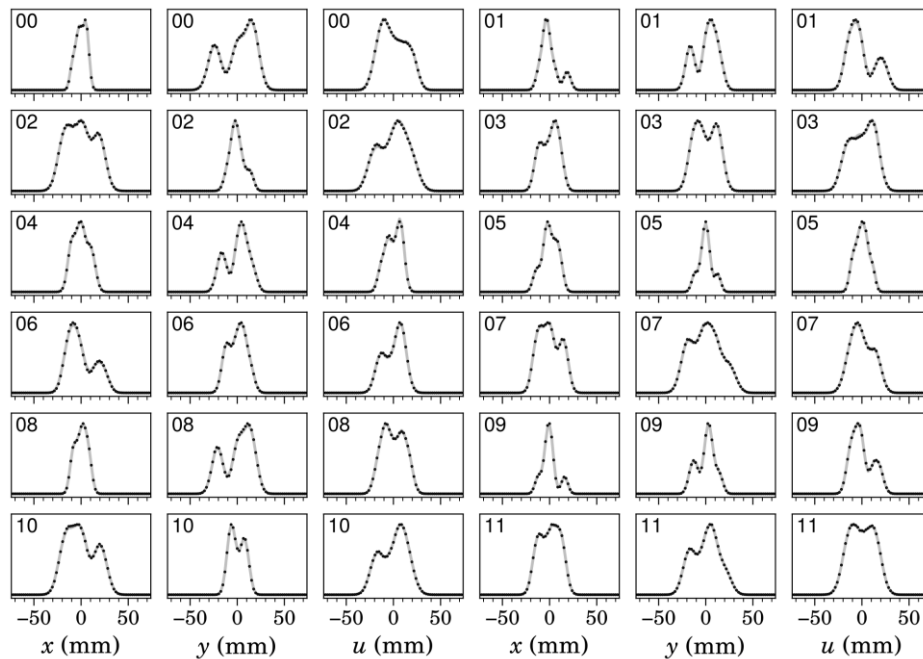
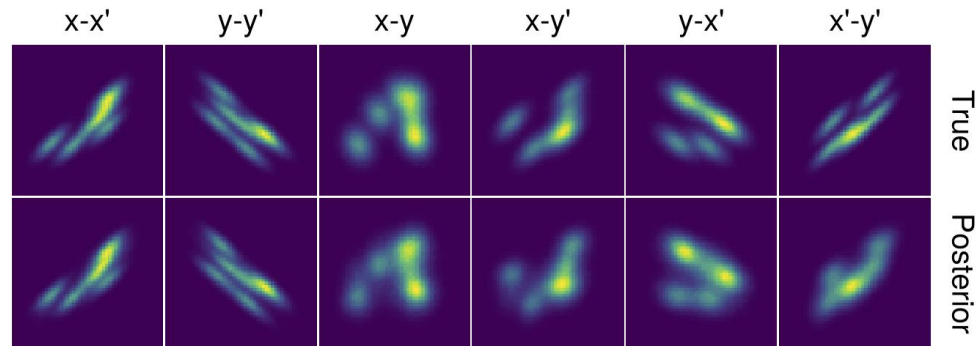
APA vs. NAFF tunes during compression



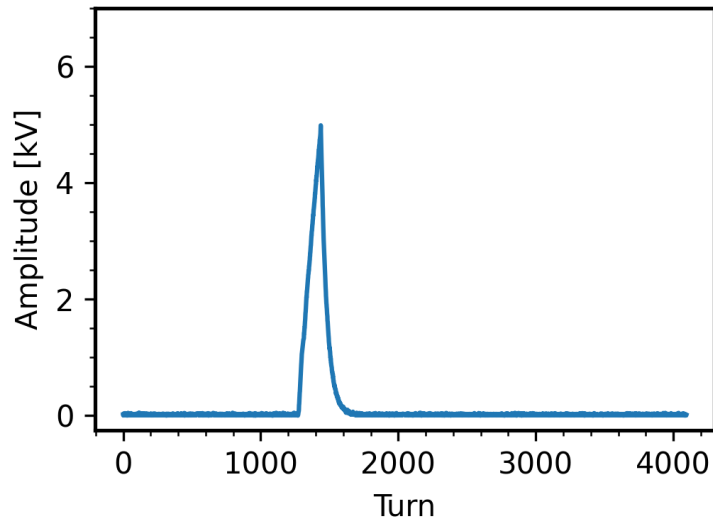
APA vs. NAFF tunes during compression



MENT reconstruction reproduces primary distribution features



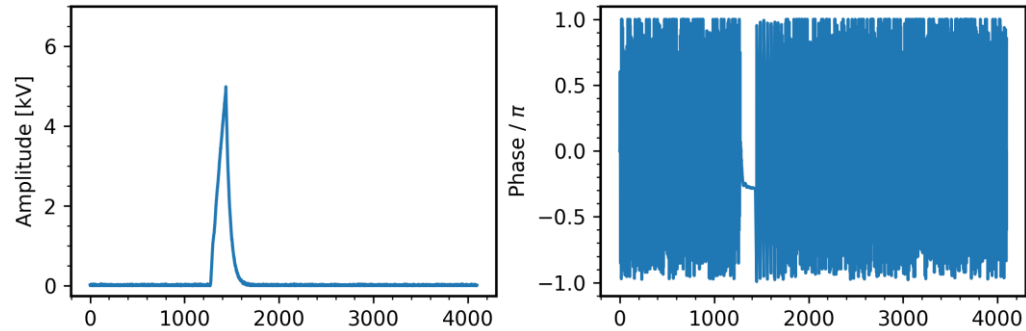
Accumulated beam induces voltage/phase shift in RF cavities



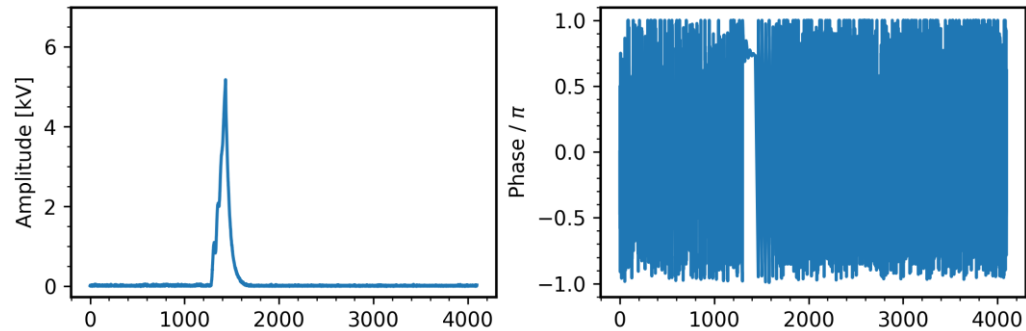
150-turn accumulation
 $R_{\text{shunt}} \sim 800 \, \Omega$
Open-loop operation

RF feedforward correction tested at low intensity

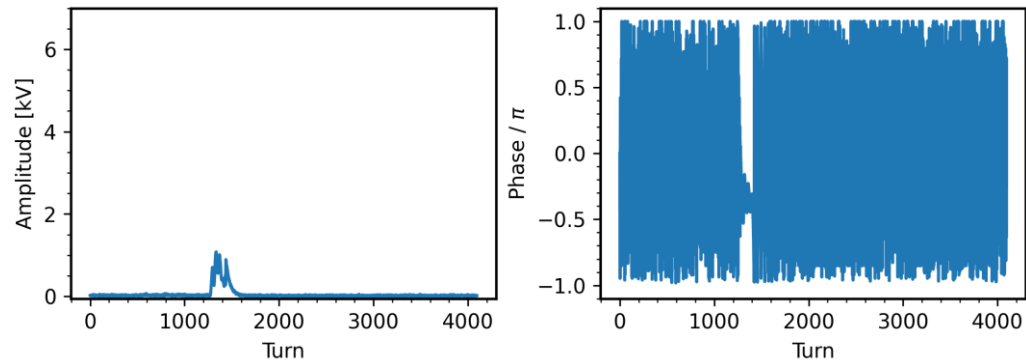
Beam-induced voltage



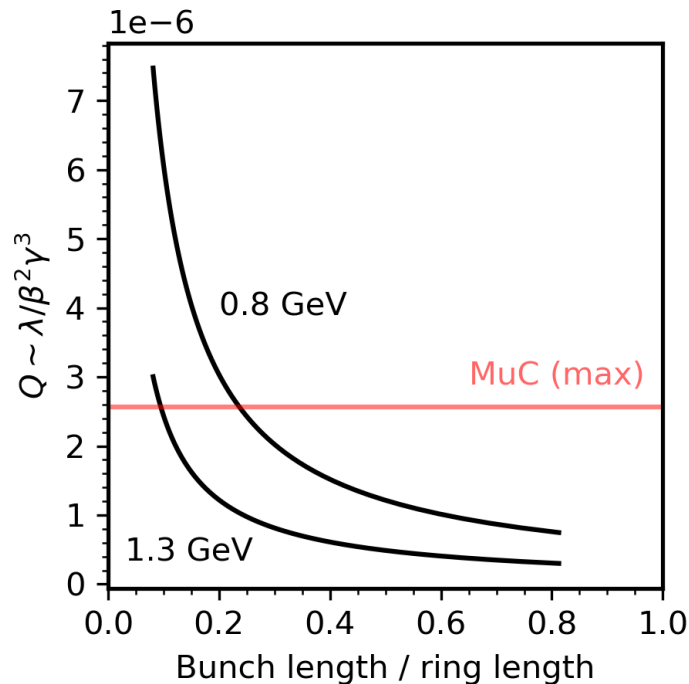
Feedforward waveform
(shifted phase)



Combined waveform



SNS space charge perveance could approach compressed bunch in MuC



MuC assumptions:

Power = 2.0 MW

Energy = 5 GeV

Rep. rate = 5 Hz

Bunch length (rms) = 2 ns

*Note that tune shift scales with emittance

Second-harmonic cavities may help reduce tails in compressed bunch

