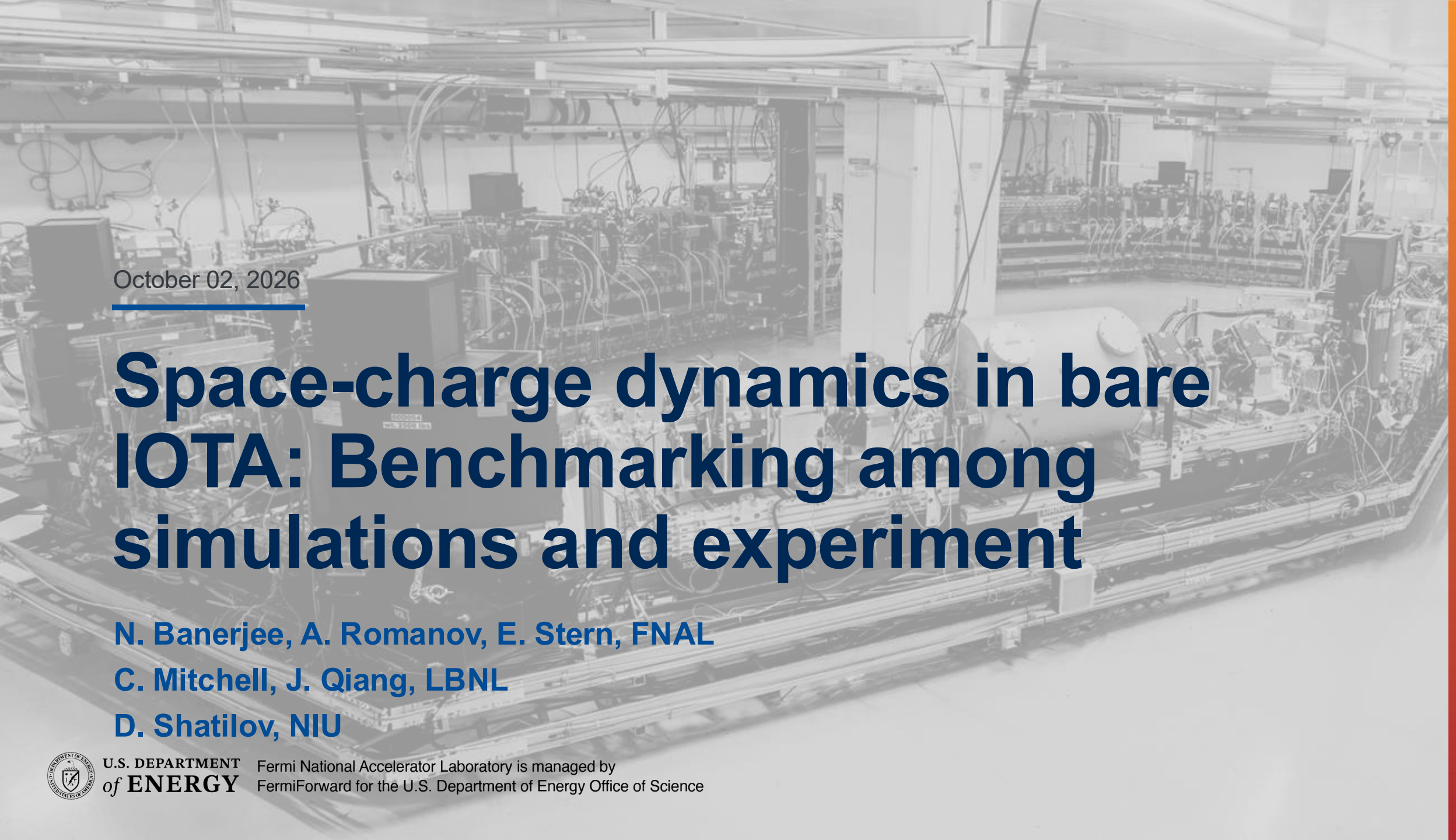


October 02, 2026

Space-charge dynamics in bare IOTA: Benchmarking among simulations and experiment

N. Banerjee, A. Romanov, E. Stern, FNAL

C. Mitchell, J. Qiang, LBNL

D. Shatilov, NIU

U.S. DEPARTMENT of ENERGY

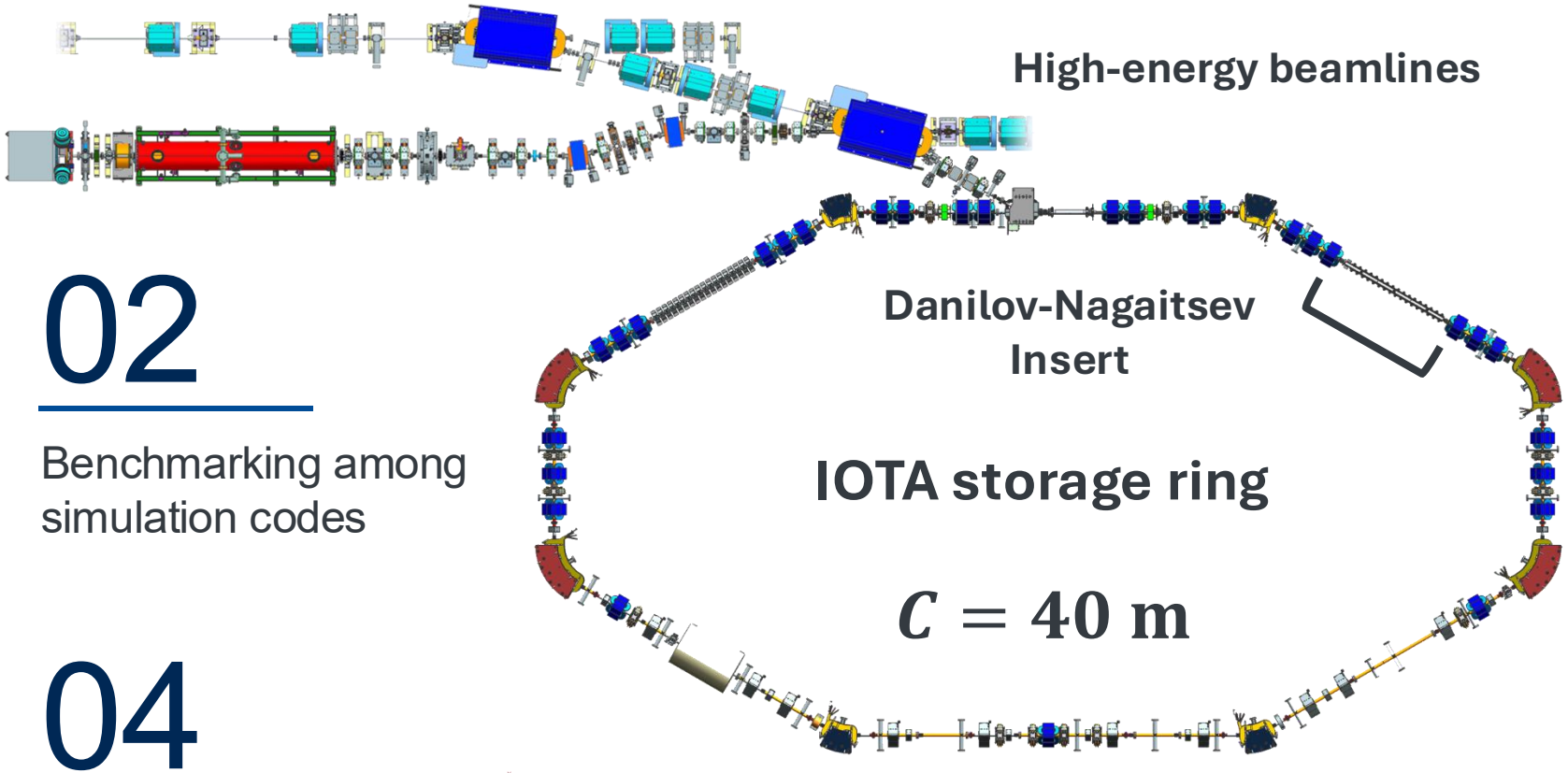
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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Overview: Fermilab Accelerator Science and Technology Facility

150 MeV e- from FAST linac

2.5 MeV p+ from IOTA Proton Injector



01

Physics Goals

02

Benchmarking among simulation codes

03

Benchmarking simulations with experiments

04

Summary and Outlook

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Advance high-intensity physics for hadron rings

Immediate goals guided by the US Department of Energy (DOE) Accelerator and Beam Physics (ABP) Roadmap and Fermilab's Intensity-Frontier priorities.

This Talk

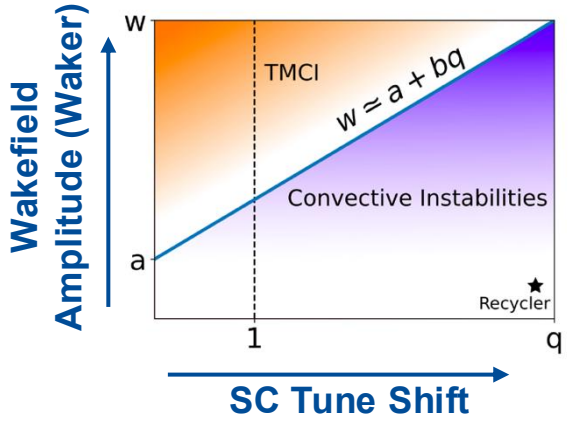
Construct model of SC dynamics in bare IOTA

Model must reproduce measured emittance growth and beam loss as a function of intensity.

Explore interplay of impedance and intense SC

Model must reproduce instability growth rates seen in experiment.

Provide methods and insights applicable to the Fermilab Booster, Main Injector, and Recycler to help establish beam to the Deep Underground Neutrino Experiment by 2031.



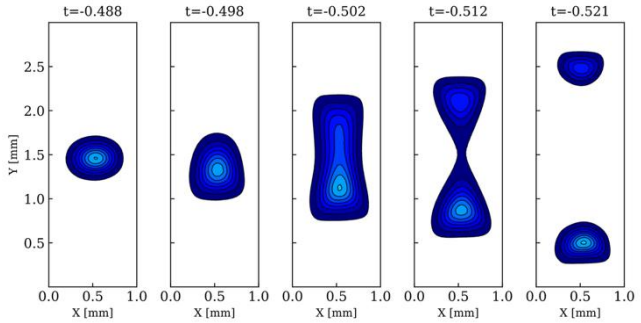
Parameter space of instabilities

A. Burov, Phys. Rev. Accel. Beams 22, 034202, 2019.

C. Gonzalez-Ortiz et al., A/25, this workshop.

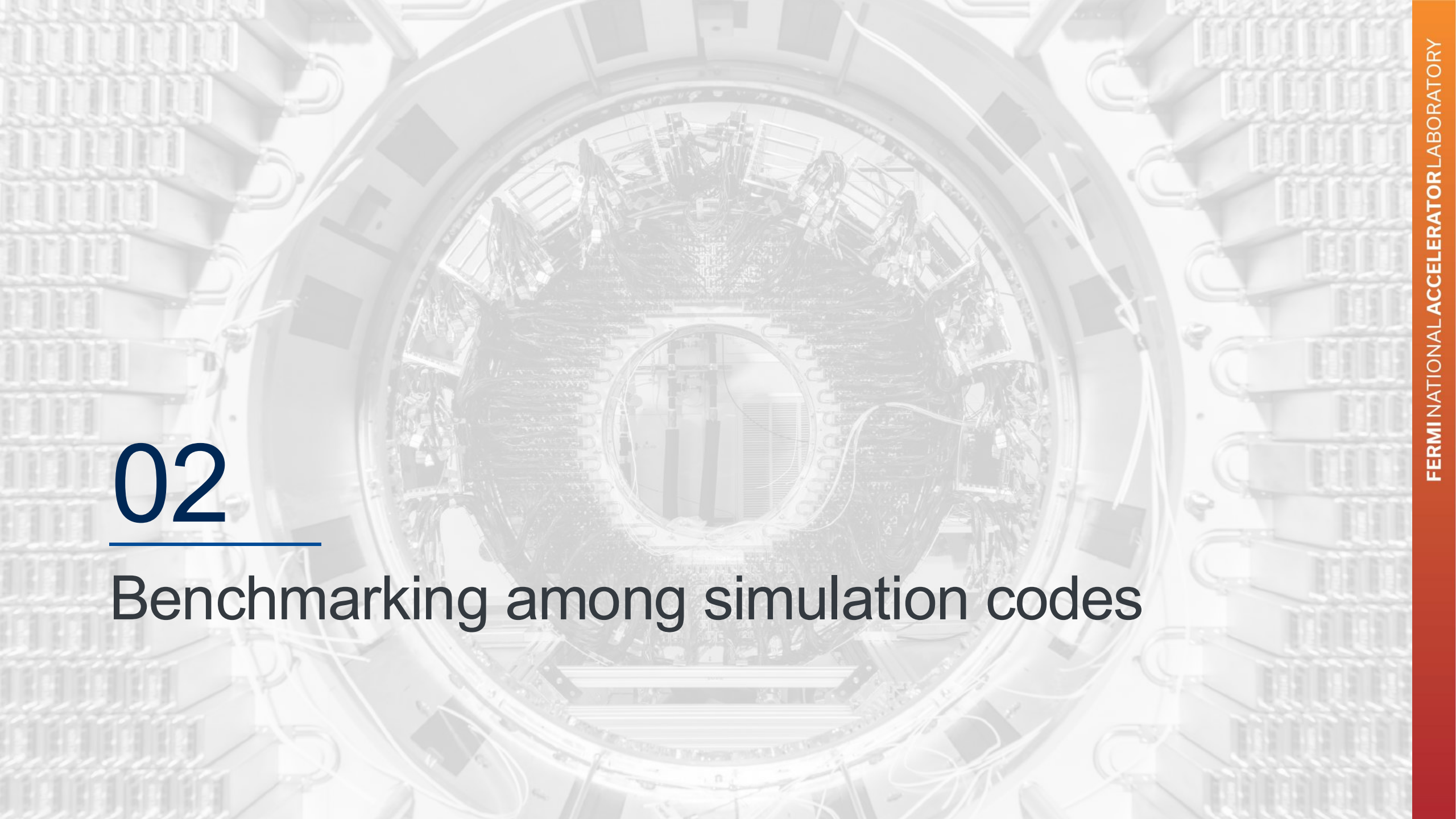
Explore Non-linear Integrable Optics as a tool to increase intensity

Experiments must show increase of collective instability threshold and lower emittance growth.



Synchrotron radiation images of 150 MeV beam passing through integer resonance with DN magnet.

J. Wieland et. al., arXiv:2607.21863, 2026.



02

Benchmarking among simulation codes

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New benchmarking campaign specific to IOTA

Captures the unique feature set of our 2.5 MeV proton physics program.

Many benchmarks exist!

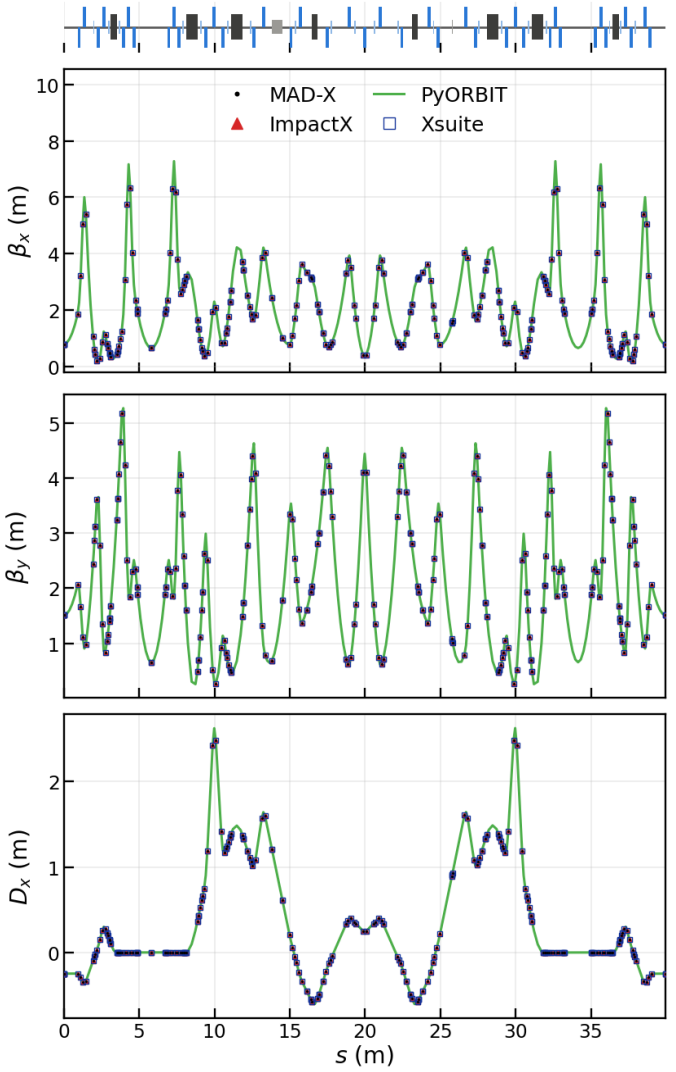
Resonance trapping with sextupoles
https://web-docs.gsi.de/~giuliano/research_activity/trapping_benchmarking/main.html
F. Schmidt et al., in Proc. HB'16, Malmö, Sweden, Jul. 2016, pp. 357-361.
Excitation of Integer Resonance
M. Titze, PhD thesis, Humboldt-Universität zu Berlin (2020), DOI: 10.18452/21423
Montague resonance and emittance exchange
I. Hofmann *et al.*, in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper MOPC003, pp. 330-332.
And many more…

Unique features of our program:

- Flexible lattice.
- Long stores – millions of turns.
- $|\Delta Q_{x,y,inc}| \leq 0.5$
- Strong bend non-linearities

Parameter	Value	Unit
Kinetic Energy	2.5	MeV
Circumference	40	m
Optics†	v8.7	
Non-linearities	Kinematic, Natural chromaticity, thick bend	
Q_x, Q_y, Q_z	$5.3, 5.3, 0.01$	
Aperture radius	25	mm
ΔQ_y @ 2 mA	- 0.48	
Macro-particles*	10^5	
SC models	Quasi-frozen, PIC 2.5 D	

NOT a detailed list!
†Dipoles and quadrupoles only. NIO, sextupoles, octupoles turned off.
***Same initial coords in all codes**



Ran four codes and two types of models

Quasi-frozen models are not much faster than PIC 2.5 D for 10^5 particles.

Processor: AMD EPYC 7543 32-Core Processor; the pod's cgroup quota is 32 CPUs and 20 GiB, shared.

GPU: NVIDIA A100 80GB PCIe, MIG slice 1g.10gb, of which 10.20 GB is usable.

	ImpactX A. Huebl et. al, in Proc. NAPAC'22, TUYE2, pp. 302-306, 2022.	Lifetrac D. N. Shatilov et al., in Proc. PAC'05, Knoxville, TN, USA, May 2005, paper TPAT084, pp. 4138-4140.	PyORBIT* A. Shishlo et al., Procedia Computer Science 51, pp. 1272-1281, 2015.	Xsuite G. Iadarola et al., in Proc. HB'23, Geneva, Switzerland, Oct. 2023, pp. 73-80.
	Processor, ms/turn	MPI ranks, ms/turn	MPI ranks, ms/turn	Processor, ms/turn
PIC 2.5 D	GPU, 562	N/A	8, 834	GPU, 1127
Quasi-frozen	GPU, 642	64, 52.5†	8, 2600	GPU, 1083

*Modified and extended: https://github.com/bcathey-fnal/py-orbit-iota

†Measured on a different cluster

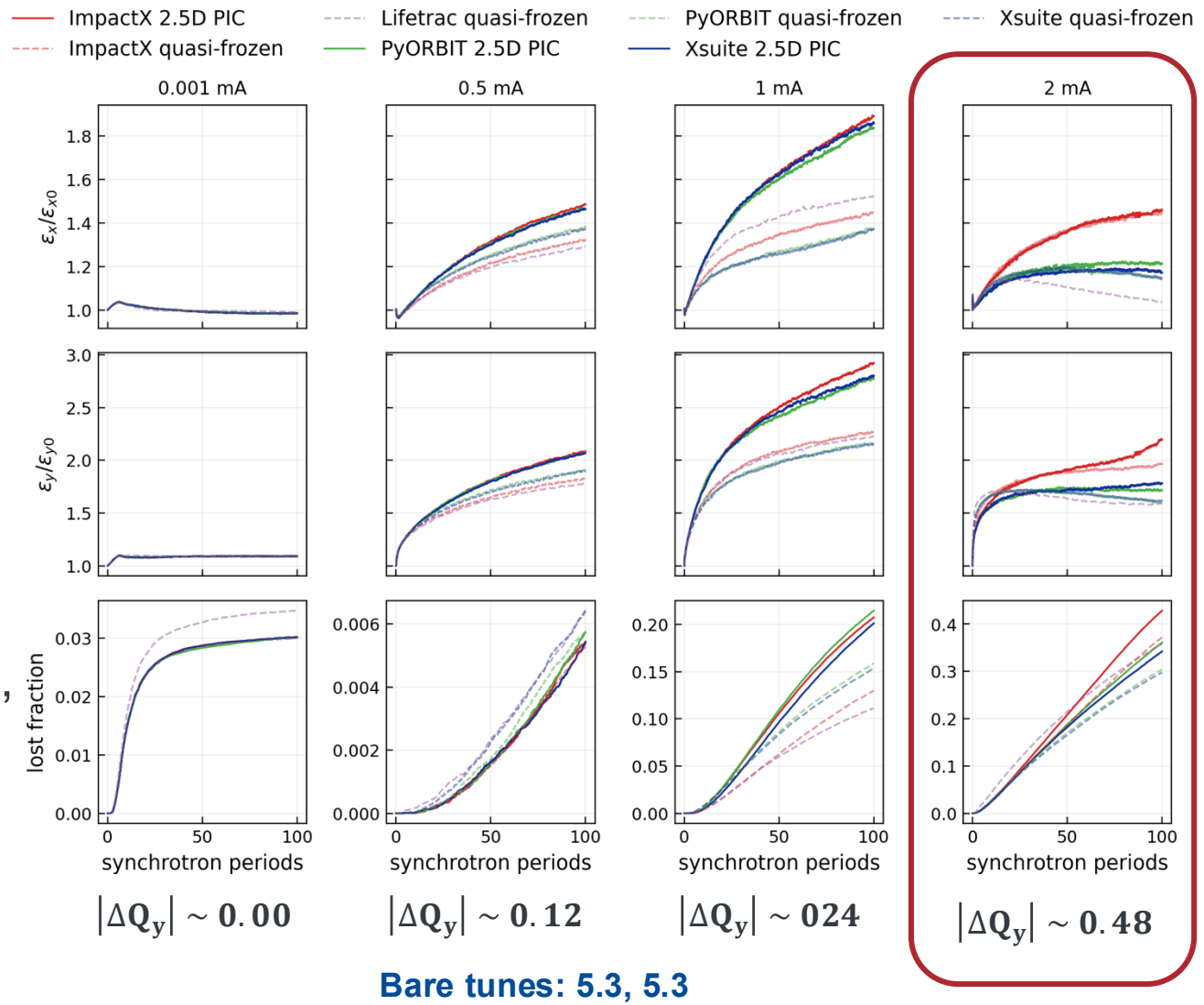
Codes generally agree with each other

But PIC and Quasi-frozen approaches diverge in rms emittance after crossing resonances.

Normal mode emittance and beam loss vs time for 100 synchrotron periods.

- Final rms emittance agrees to 15 % and loss to 0.1 % for $I < 0.5$ mA ($|\Delta Q_y| < 0.12$, $Q_y = 5.3$) over all models.
- At 0.5 mA, and 1 mA, PIC and quasi-frozen approaches diverge from each other.
- Beyond the integer resonance (2 mA), both PIC 2.5D and quasi-frozen ImpactX models diverge from others.

RMS emittance is influenced by halo.



Bare tunes: 5.3, 5.3

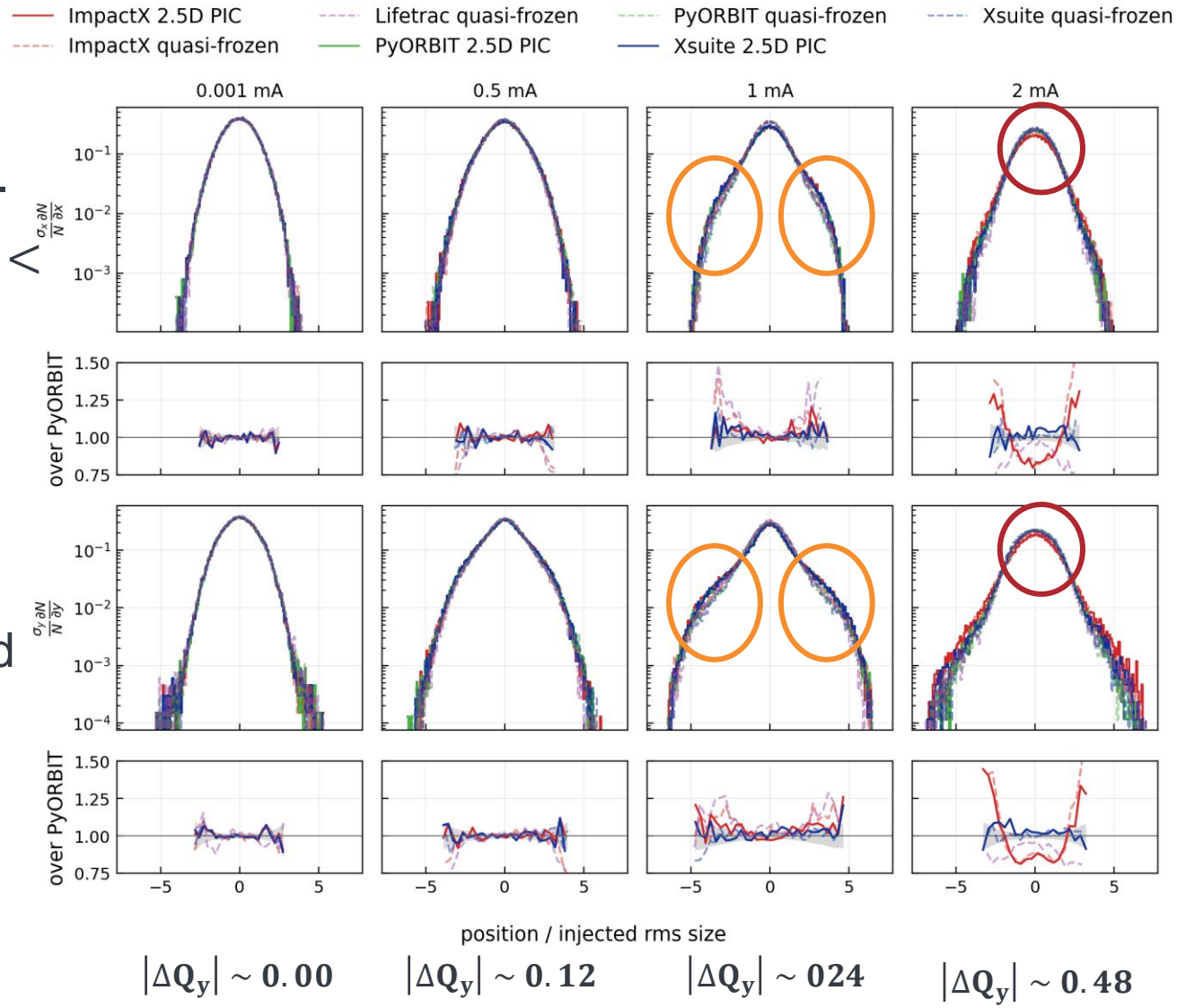
Difference in transverse beam profiles is subtle

Moderate differences only show up near or beyond the integer.

Transverse beam profiles after 100 synchrotron periods at injection position.

- Core population for $I < 0.5$ mA ($|\Delta Q_y| < 0.12$, $Q_y = 5.3$) is within statistical noise.
- At 1 mA, PIC and quasi-frozen approaches diverge from above 2σ.
- At 2 mA, the profile prediction (including the core) from PIC 2.5D and quasi-frozen ImpactX models deviate beyond noise.

Differences in the core should show up in the tune plane.



Tune footprints reveal the difference

Footprints differ in the size of the depressed tail.

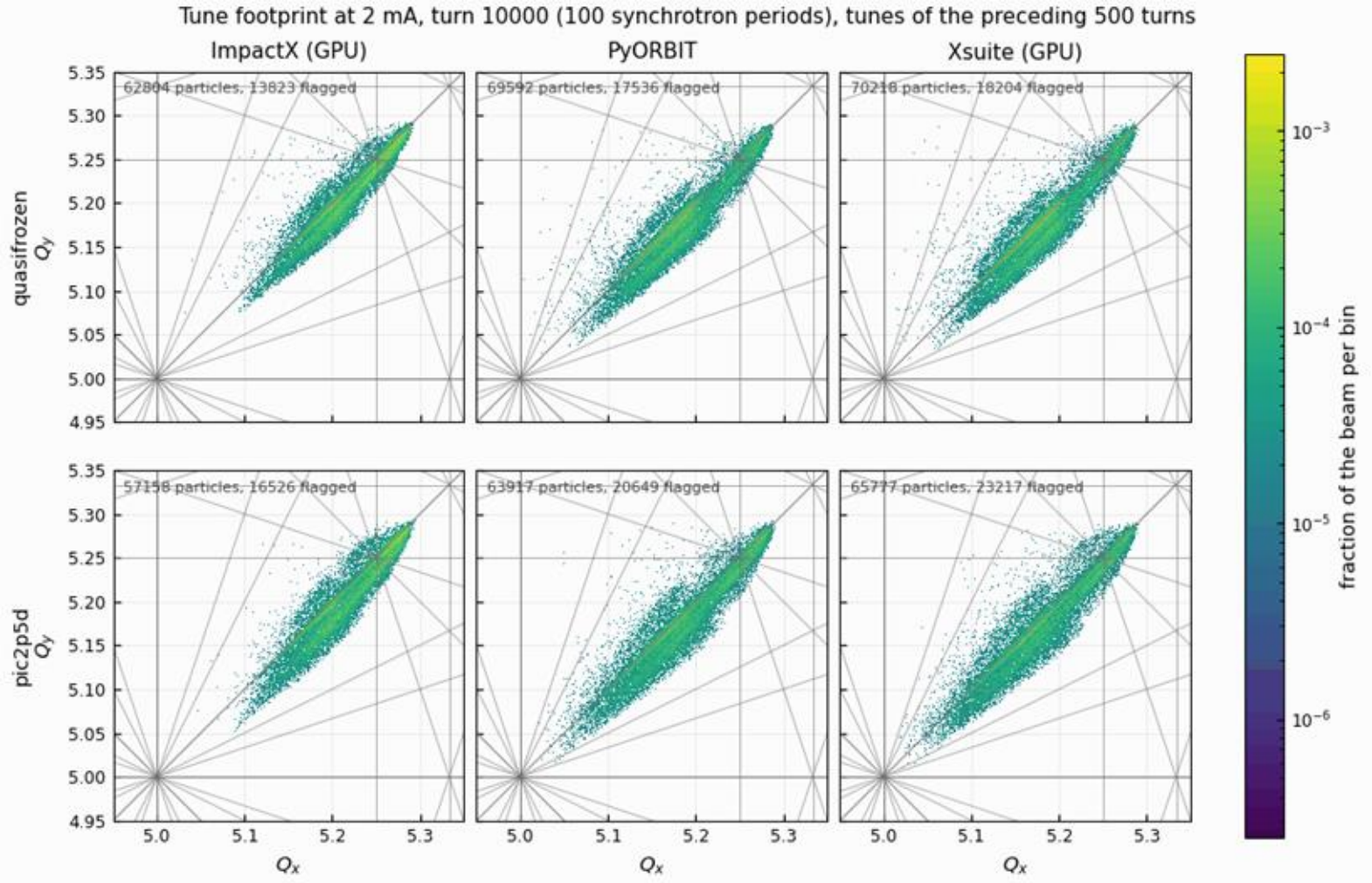
Tune footprints at 2 mA.

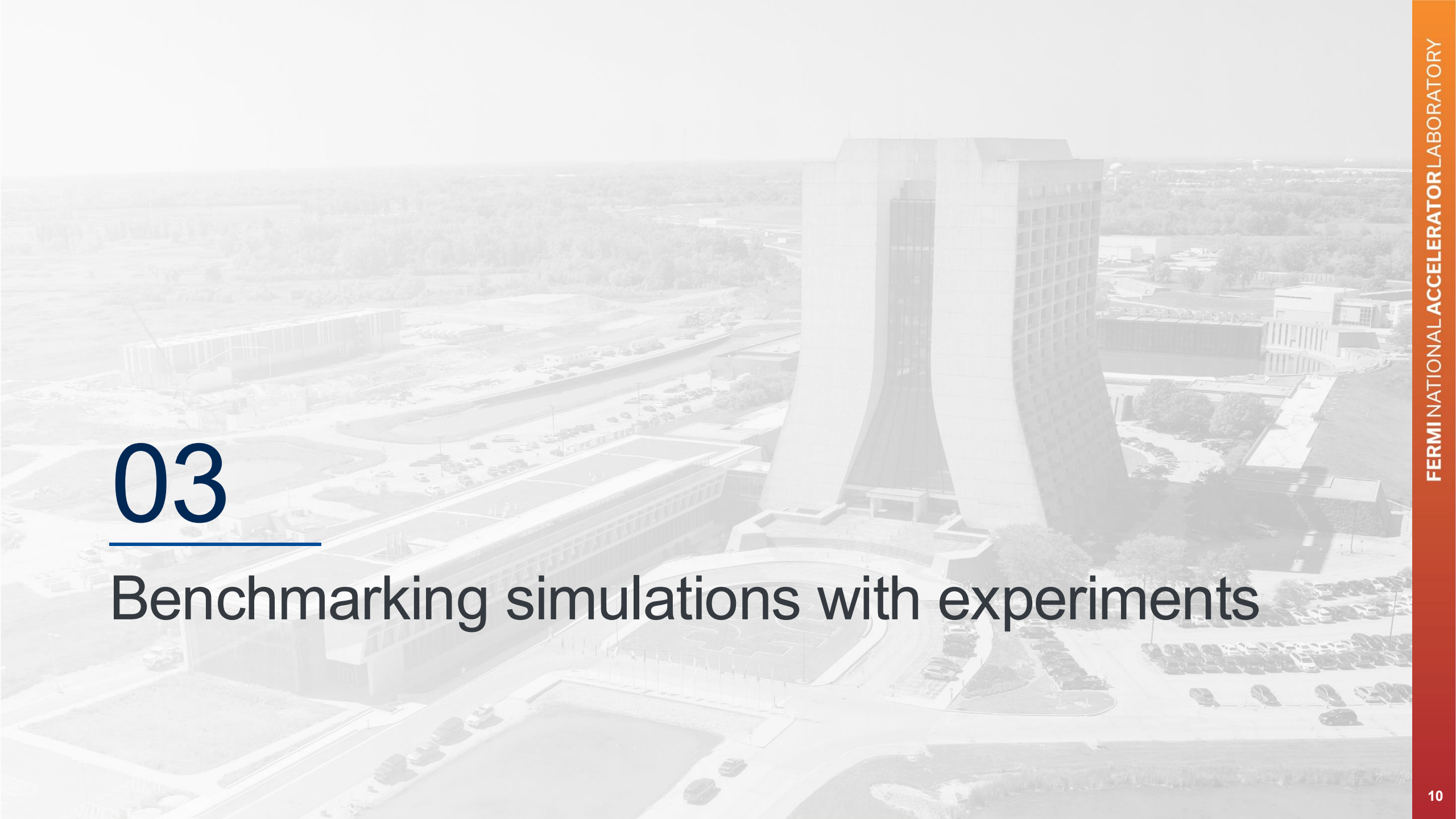
- Signature of

$$2Q_x - 2Q_y = 0$$

- Good agreement between both quasi-frozen and PIC models in PyORBIT and Xsuite.
- Tune depression is slightly different in ImpactX.

Motivates the need for a detailed comparison table of all modelling choices in all codes.





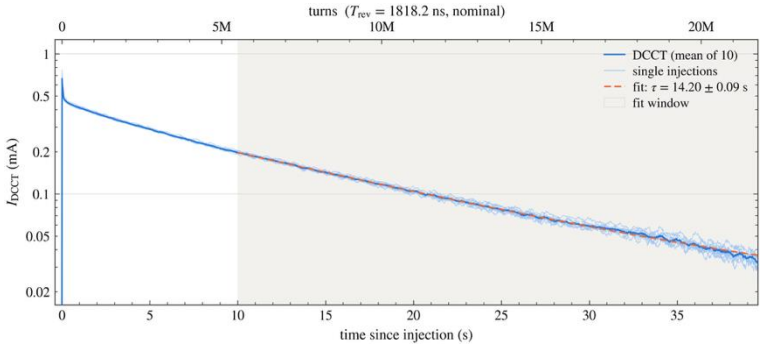
03

Benchmarking simulations with experiments

Compare loss with coasting beam

Captures the interplay of space-charge and magnet non-linearities.

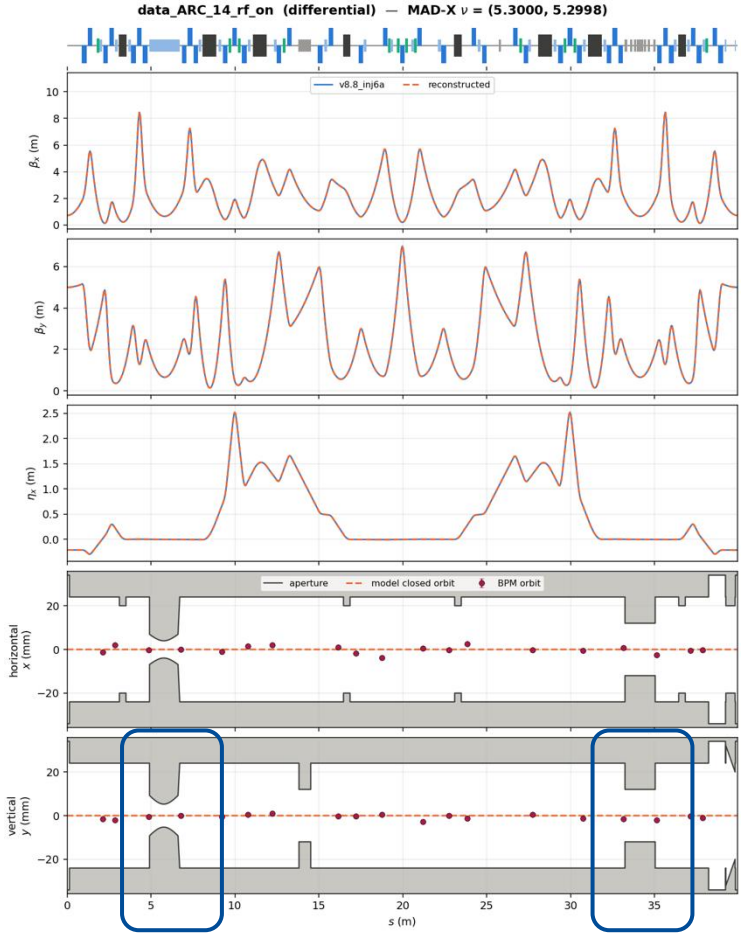
First protons circulated in January 2026.



Available diagnostics:

Only data from DCCT has been used in this benchmark.

Parameter	Value	Unit
Momentum	70	MeV/c
Circumference	40	m
Optics†	v8.8 + LOCO + 65 tune knob values	
Non-linearities	Kinematic, chromaticity, thick bend, bend multipole, quad fringe	
Q_x, Q_y, Q_z	$5.3 \pm 0.1, 5.3 \pm 0.1, 0.0$	
Aperture radius	realistic	
ΔQ_y @ 8 mA	- 0.28 (nominal)	
Macro-particles*	10^5	
SC models	Quasi-frozen, PIC 2 D	



NOT a detailed list!

†Dipoles and quadrupoles only. NIO, sextupoles, octupoles turned off.

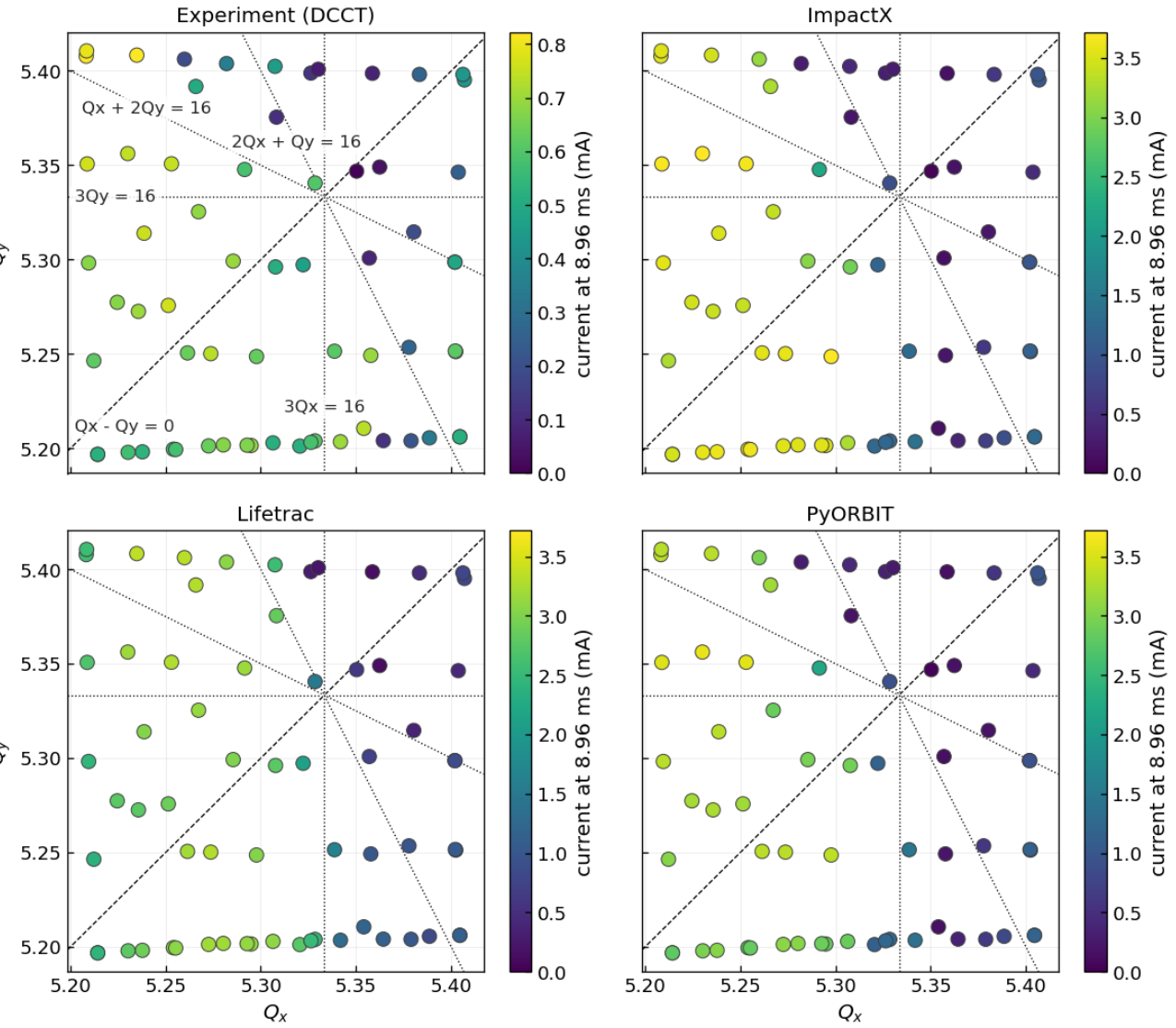
***Same initial coords in all codes**

Models reproduce the general tune landscape

But a single loss figure hides temporal complexity.

Beam current after 5000 turns as measured in the machine, and predicted by ImpactX, Lifetrac, and PyORBIT over the tune plane–Static tune scan driven by Bayesian Exploration.

- Both PIC 2D and quasi-frozen models closely agree on the distribution of loss on the tune plane.
- General agreement of larger beam loss near $3Q_x = 16$ among experiment and simulations. But raw current values are different.

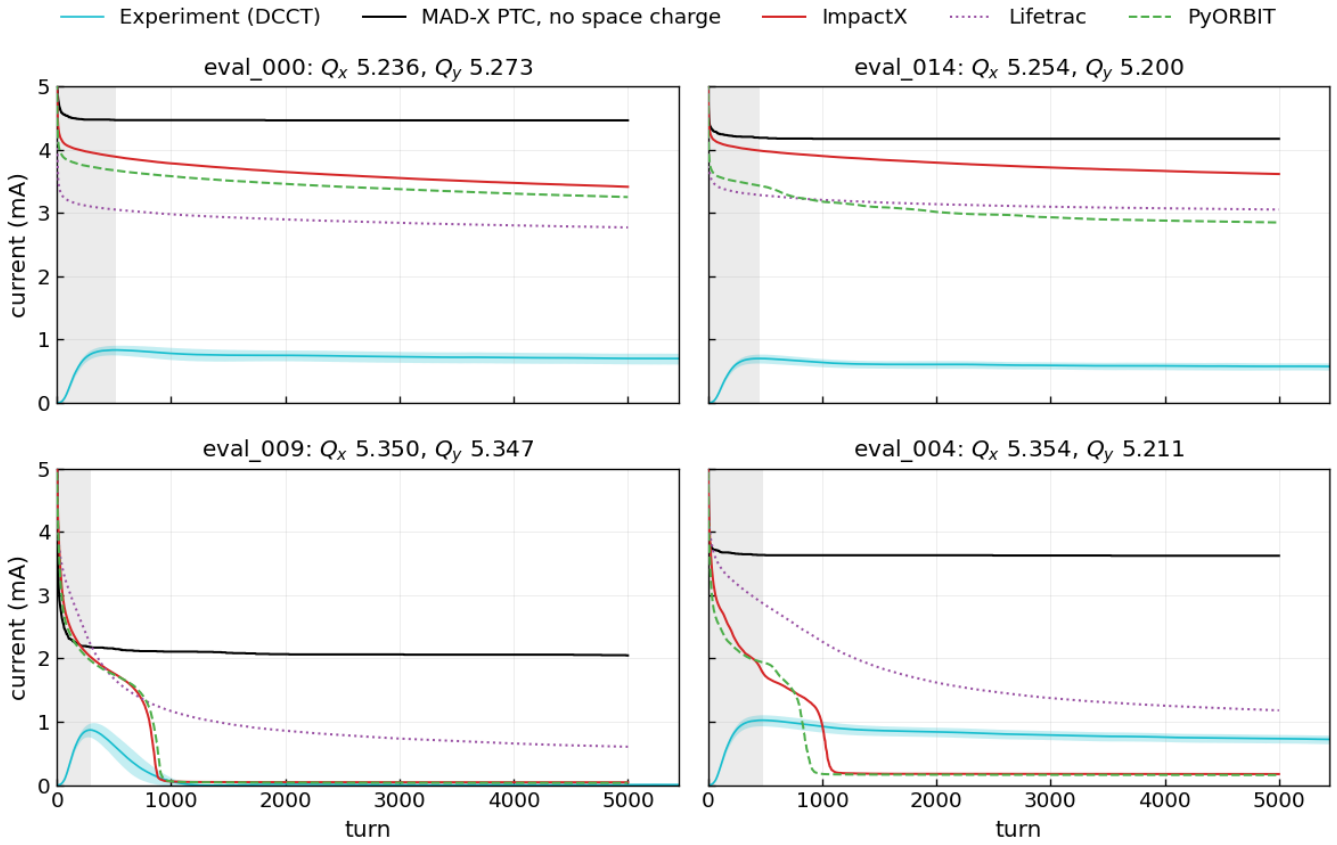


Space-charge generates steady beam loss

Models reproduce this effect qualitatively, but PIC 2D adds delayed loss unseen in experiment.

- The simulated ring loses about 50% of the current within a few turns after injection due to scraping on the aperture.
- Only space-charge simulations reproduce steady beam loss over 1000s of turns.
- Simulations near 3Qx = 16 show delayed increase in beam loss not seen in experiment.

Opportunity to improve match by tuning beam parameters and multipole strength. – Model calibration



04

Summary and Outlook

Summary

The immediate goals of the IOTA proton research program will address these challenges in the context of hadron rings.

1. Construct high-fidelity model of space-charge dynamics in bare IOTA.
2. Explore the interplay of impedance and space-charge.
3. Explore Non-linear Integrable Optics as a tool to increase intensity in future machines.

Time-scale for goals: 2 proton runs

A new simulation benchmarking campaign specific to bunched proton beam in IOTA reveals differences among different codes, especially on crossing resonances.

A detailed comparison table of all modelling choices in all modern codes will help the field.

While simulations of loss with coasting beam qualitatively match experimental data, quantitative agreement will require extensive model calibration.

Improving model calibration techniques through targeted experiments will improve model fidelity.

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Acknowledgements and an invitation

We would like to thank Rob Ainsworth, Sergey Antipov, Alexey Burov, Brandon Cathey, Valery Lebedev, Sergei Nagaitsev, Frank Schmidt, Tanaji Sen, Ben Simons, Giulio Stancari, Alexander Valishev, Mike Wallbank, and John Wieland for insightful discussions, for help with modeling and simulations, and for contributing to the definition of the IOTA proton physics program.

Visit us and run an experiment in IOTA! Our unique capabilities include having:

- **highly reconfigurable optics,**
- **tolerance for large beam loss,**
- **abundant beam time, and**
- **capability of reaching an incoherent tune shift of 0.5 with 2.5 MeV protons.**

This work was produced by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

05

Backup slides

Appendix A: Future Goals: Demonstrate space-charge compensation, snap bunch rotation…

Space-charge resonance suppression

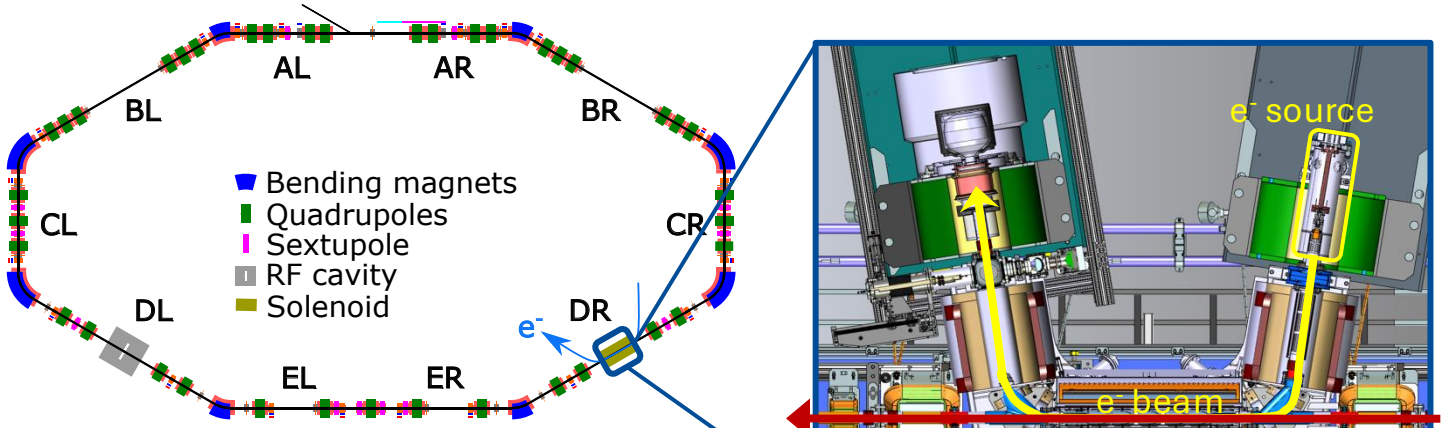
- Adjusting multipoles.
- Realize 2-fold periodicity.

Electron lens

- Implementation of NIO using the McMillan and Gaussian electron lens.
- Demonstration of space-charge compensation.
- Electron Cooling to control equilibrium tune shift.

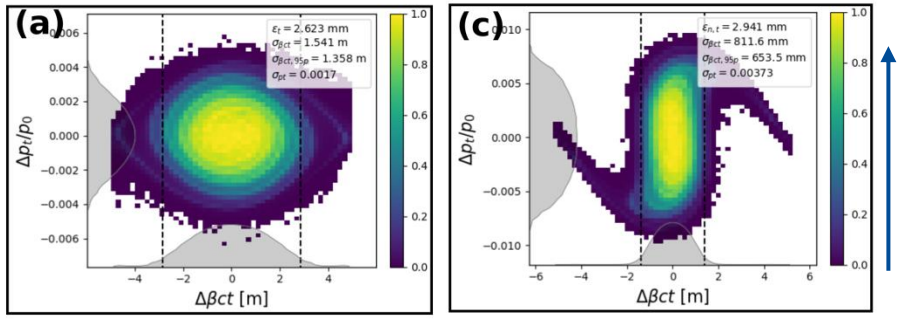
Snap bunch rotation

Needed for the muon collider proton driver.



Proposed location of the electron lens in IOTA

G. Stancari et al, JINST 16 P05002, 2021.



Relative momentum deviation

Longitudinal spatial coordinate

Simulated longitudinal phase-space for a factor of 2 snap bunch rotation at 0.5 mA in IOTA.

B. Simons et al., Accepted for publication in JINST, 2026.

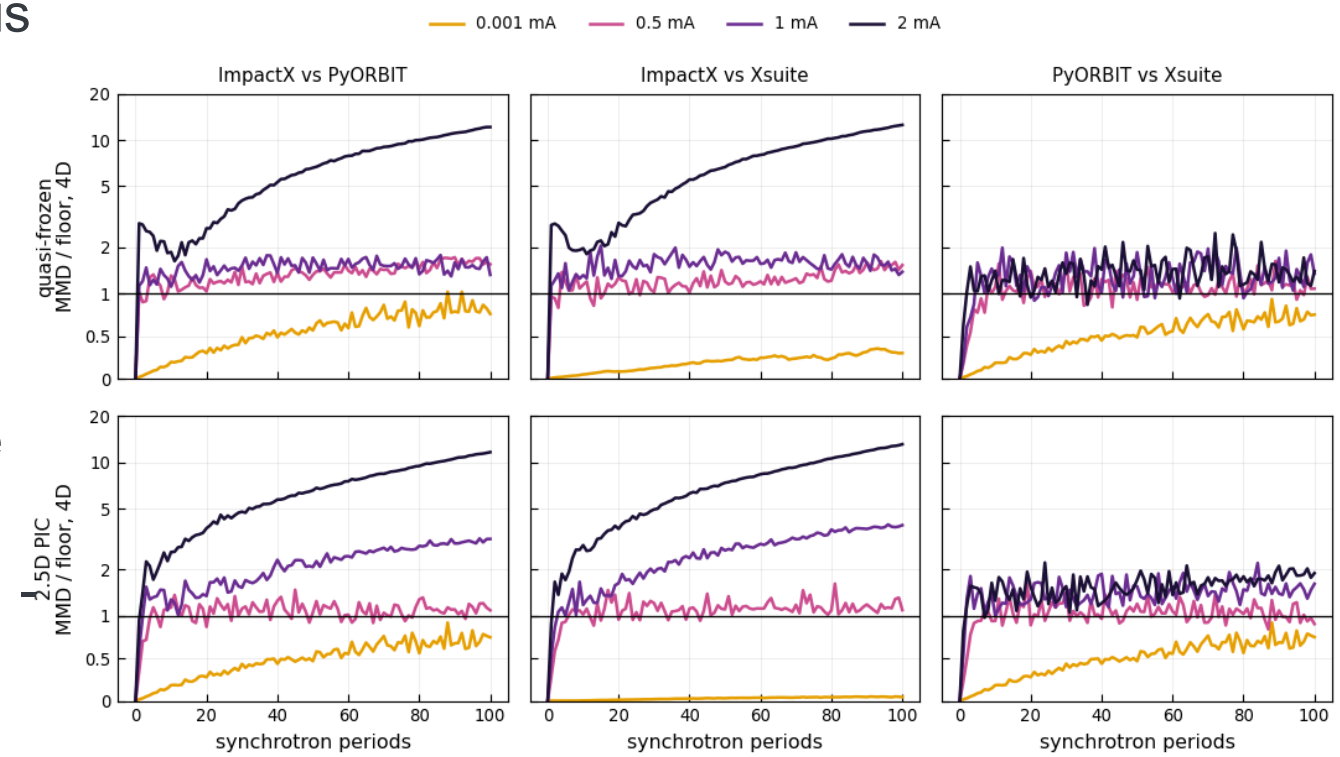
Appendix B: MMD quantifies the difference

Statistical measures can be used to track the deviation among different models

Maximum Mean Discrepancy (MMD) is a statistical measure of the distance between two probability distributions.

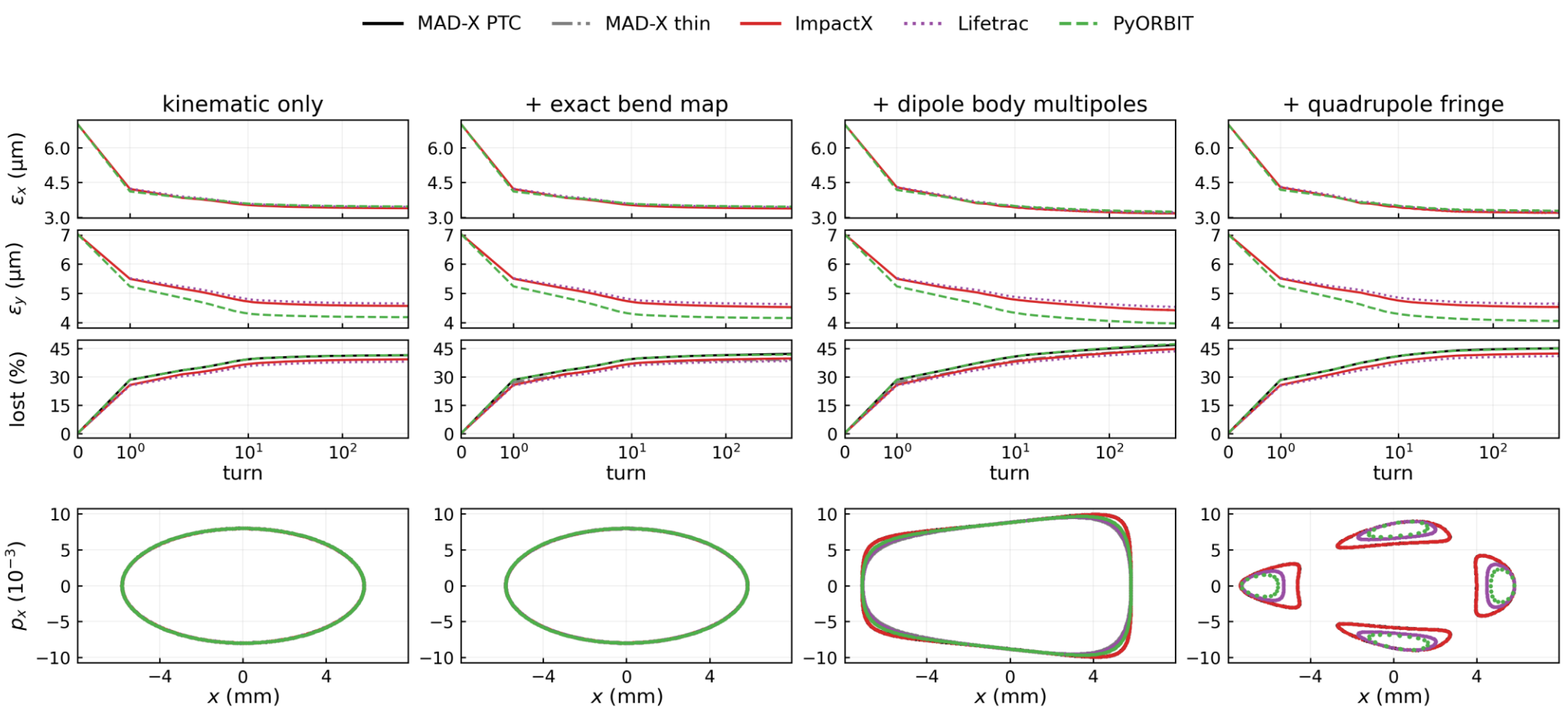
C. Mitchell et al., Phys. Rev. E 106, 065302, 2022.

- At 1 uA, the metric is below the sampling floor for all codes and models, but ImpactX and Xsuite are the best matched.
- PyORBIT and Xsuite match within 1 2 times the sampling floor at all currents, while ImpactX deviates.



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Appendix C: Single particle dynamics with lattice non-linearities



Appendix D: Delayed loss seen in simulations of coasting beam

