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INCOHERENT DYNAMICS OF INTENSE PROTON BEAMS UNDER ELECTRON COOLING

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Abstract

The minimum emittance of ion beams achieved using electron cooling is limited by the heating processes of Intra Beam Scattering and diffusion driven by resonance crossing of particles due to space-charge. We describe a new experiment to explore the intense space-charge regime with a transverse tune shift approaching -0.5 using 2.5 MeV protons at the Integrable Optics Test Accelerator (IOTA) at Fermilab. We also report on the results from PyORBIT simulations incorporating transverse space-charge and electron cooling with emphasis on the incoherent dynamics of the particles.

INTRODUCTION

The four grand challenges identified by the accelerator and beam physics community in a recently published roadmap [1] are improving beam intensity, quality, control and prediction in particle accelerators. When applied to hadron rings, increasing beam current requires a better understanding of collective effects and mechanisms of beam loss. Improving beam quality requires better grasp of incoherent motion of particles inside a bunch and development of strong cooling systems. Better beam control involves the development of control and detection of the beam at the single particle level. Lastly, enhancing beam prediction requires fast and high-fidelity numerical models incorporating all relevant beam physics. The Integrable Optics Test Accelerator (IOTA) [2, 3] in Fermilab was built for research into various aspects of beam physics and hosts experiments which addresses the grand challenges facing the community.

Projects at IOTA include demonstration of Non-linear Integrable Optics (NIO) [4, 5] for enhanced Landau damping, Optical Stochastic Cooling [6, 7], 6D phase space diagnostics [8], single electron tracking [9, 10] and the electron lens [11] for NIO and space-charge compensation. In this paper, we discuss a dedicated electron cooling configuration for the electron lens system in IOTA to study both incoherent and collective motion of 2.5 MeV protons with intense space-charge. The research aims to address the challenges of increasing beam intensity, quality and better prediction. Specifically, we will study the maximum attainable limit of space-charge tune shift in hadron rings [12, 13] with electron cooling as a knob to control equilibrium phase-space distributions. In addition, we will also use the data to benchmark various space-charge codes. The research program also includes the *waker* experiment [14–16] to study the interplay of collective instabilities and space-charge, with cooling serving as knob to control the incoherent tune shift.

In the next section, we outline the machine parameters and lattice used for electron cooling experiments with intense space-charge. Then we show some results from numerical simulations and motivate our planned experiments. Finally, we summarize our work and list next steps.

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Table 1: Typical Operation Parameters for Protons in IOTA

Parameter	Value		Unit
Kinetic energy (K_b)	2.5		MeV
Emittances ($\epsilon_{x,y}$)	4.3, 3.0		μm
Momentum spread (σ_p/p)	1.32×10^{-3}		
	Coasting	**Bunched**	
Number of bunches	-	4	
Bunch length (σ_s)	-	0.79	m
Beam current (I_b)	5.79	1.15	mA
Bunch charge (q_b)	10.6	0.52	nC
Tune shifts ($\lvert\Delta\nu_{x,y}\rvert$)	0.33, 0.50		
$\tau_{\text{IBS,x,y,z}}$	10.2, 2.62, 301	14.4, 3.70, 424	s

MACHINE SETUP

IOTA is designed to circulate both electrons up to an energy of 150 MeV and protons with a kinetic energy of 2.5 MeV ($pc \approx 70$ MeV). While electrons encounter negligible space-charge forces, proton operations are designed to achieve incoherent betatron tune shifts approaching -0.5. The injector [17] will produce protons in a duoplasmatron source and accelerate them using a Radio Frequency Quadrupole to a kinetic energy of 2.5 MeV with typical beam parameters listed in Table 1. Once the beam enters IOTA, we can either let it debunch in the ring for coasting beam experiments or rebunch it using a wide-band rf cavity operating at harmonic number 4. The transverse linear optics of the IOTA ring shown in Fig. 1 is optimized for zero dispersion at the electron cooler, the injection kicker and the rf cavity. The beta functions are matched into the cooler solenoid and skew-quadrupoles are used to compensate for transverse coupling. In addition, the lattice design has adjustable betatron tunes $Q_x \in [4.0, 4.25]$ & $Q_y \in [3.0, 3.50]$. The

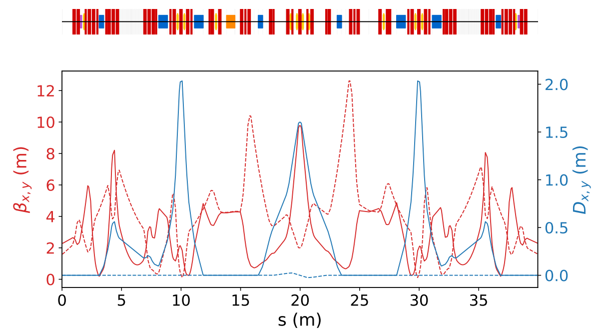

Figure 1: Amplitude (red) and dispersion (blue) as functions of s position for the IOTA electron cooling lattice. The solid and dashed lines represent x and y directions respectively.

Table 2: Electron Cooler Parameters for IOTA

Parameter	Values		Unit
Proton parameters			
RMS Size ($\sigma_{b,x,y}$)	4.43, 3.70		mm
Main solenoid parameters			
Magnetic field ($B_{\parallel}$)	0.1 - 0.5		T
Length (l_{cooler})	0.7		m
Flatness ($\langle B_{\perp}\rangle / B_{\parallel}$)	2×10^{-4}		
Electron parameters			
Kinetic energy (K_e)	1.36		keV
Temporal Profile	DC or pulsed		
Transverse Profile	Flat		
Source temp. (T_{cath})	1400		K
Current (I_e)	1.7	80	mA
Radius (a)	14	18	mm
$\tau_{\text{cool,x,y,s}}$	7.6, 6.5, 5.3	2.5, 2.4, 1.4	s

minimum emittance growth time-scales due to Intra-Beam Scattering (IBS) calculated using MAD-X [18] at a vertical incoherent tune shift of 0.5 is a few seconds. The large emittance growth rate for protons necessitates the use of electron cooling to extend beam lifetime during experiments.

We have proposed two electron cooler configurations for proton experiments at IOTA: a weak configuration using a low-current pulsed electron source for experiments with low bunch charge, and a strong configuration with larger current for use in studies requiring large incoherent tune shifts. Table 2 lists the parameters for the magnetized electron cooler configurations, both employing electrostatic thermionic electron sources [19] and a superconducting main solenoid [20] capable of 0.5 T in the cooling region. The corresponding cooling times as predicted by the Parkhomchuk model [21] are shorter than the expected emittance growth time-scales from IBS.

SIMULATIONS OF SPACE-CHARGE AND ELECTRON COOLING

We use a transverse Particle-in-Cell space-charge model in PyORBIT [22] along with an extension which implements the Parkhomchuk cooling force to simulate incoherent dynamics of the proton beam under intense space-charge. The details of the simulation setup including the cooling model, space-charge model parameters and adiabatic charge ramping for injection are described in previous proceedings. [23, 24]

Figure 2 shows the results from two simulations of coasting beam at the same emittance but different currents, demonstrating the effect of electron cooling and its limit. We obtain the maximum transverse incoherent tune shifts $|\Delta\nu_{x,y}|$ of the coasting beam from the knowledge of the linear lattice functions as follows,

$$|\Delta\nu_{x,y}| = \frac{r_p I}{2\pi\beta^3\gamma^3 cq} \int \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x + \sigma_y)} \, ds\,, \quad (1)$$

where $\sigma_{x,y} = \sqrt{\epsilon_{x,y}\beta_{x,y} + \sigma_\delta D_{x,y}}$ are the transverse rms beam sizes as a function of s position, $\beta_{x,y}$ and $D_{x,y}$ are the amplitude and dispersion functions respectively. I, $\epsilon_{x,y}$ and σ_δ are the beam current, transverse rms emittances and rms momentum spread respectively. Figure 2(a) reveals that if we start with an incoherent tune shift of 0.1 (orange curve) then the cooler can boost the tune shift beyond 0.2. While if we start with a tune shift of 0.25 (green curve), then the system reaches equilibrium at a tune shift of $\approx$ 0.23. Further the probability distribution of particles in the x-coordinate at the end of the simulation displayed in Fig. 2(b) for I = 2.90 mA shows significant transverse diffusion with respect to the initial distribution (blue) while the particles for I = 1.16 mA shows much less diffusion. This indicates that the rate of diffusion driven by particles crossing resonances due to space-charge tune depression increases with beam current. This limits the minimum attainable emittance with a fixed cooling rate. An experiment designed to verify such a dependence of equilibrium emittance as a function of beam current at different cooling rates will quantify the diffusion rates driven by space-charge and serve as a good benchmark for simulations.

The resonance crossing of particles is dependent on the position and the area of the beam footprint in the tune plane. While the size of the footprint is controlled by chromaticity, lattice non-linearities and space-charge, the position is governed by the bare lattice tune. One way of quantifying the space-charge limit in a ring is to measure beam loss as a function of transverse tunes [13] of the linear lattice. Figure 3 shows the results of such a simulation study done for a coasting beam of I = 2.9 mA corresponding to a vertical space-charge tune shift of 0.25. Over the given betatron tune range of 0.25 in both planes, the cumulative beam loss over 1000 turns for an error-free lattice is close to 0 except near the integer resonances. Similar studies in real IOTA, measuring beam loss and emittance growth as a function of working point of the bare lattice in both planes will yield insights on incoherent dynamics without direct

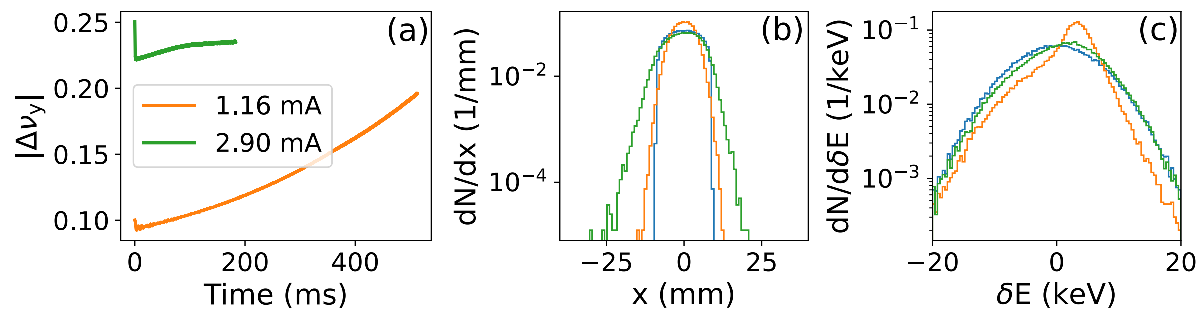

Figure 2: Results from simulations of electron cooling with space-charge in PyORBIT at two different coasting beam currents: 1.16 mA (orange) and 2.90 mA (green). (a) Vertical incoherent tune shift as a function of time. (b), (c) Normalized histograms of the x and δE coordinates of the macro-particles respectively at the end of the simulation. The blue curve in the histograms represent the initial condition.

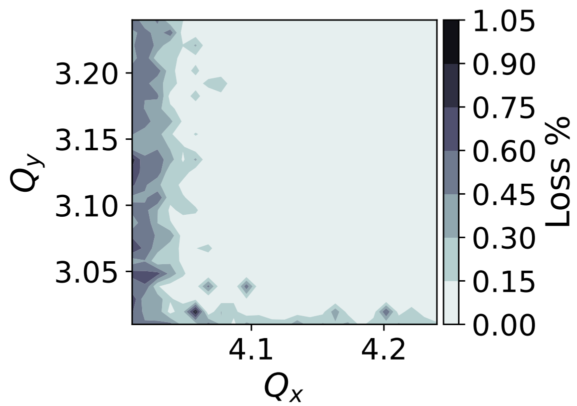

Figure 3: Cumulative beam loss over 1000 turns at a beam current of 2.9 mA as a function transverse tunes of the bare lattice.

measurement of the tune distribution.

CONCLUSION AND OUTLOOK

In this paper, we presented the design of an electron cooling experiment with 2.5 MeV protons at the Integrable Optics Test Accelerator in Fermilab. Using this setup we will conduct experiments on incoherent dynamics, collective motion and benchmarking simulations in an effort to address the three grand challenges of improving beam quality, intensity and prediction respectively. Our design uses two electron coolers. The weak cooler with cooling times of the order of 10 seconds will operate in the small tune shift regime to extend beam lifetime by compensating for emittance growth due to IBS. The strong cooler with cooling times of a few seconds will compensate for particle diffusion due to resonance crossing driven by space-charge tune shifts in addition to compensating for IBS which has growth times of a few seconds at the maximum vertical incoherent tune shift of 0.5. We demonstrate some examples of incoherent dynamics using simulations of coasting beam done in PyORBIT which uses a 2.5D space-charge model along with the Parkhomchuk model of electron cooling. The results indicate that measuring equilibrium emittance and beam loss as functions of total current and bare lattice tunes will provide insight in improving beam quality and prediction. Future work will involve higher resolution PIC simulations for more turns, analysis of lattice errors and tolerances, benchmarking current results with other space-charge codes and including IBS models into the PyORBIT code. These will result in concrete experimental plans and engineering design of the apparatus.

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REFERENCES

[1] J. Blazey *et al.*, "Accelerator and Beam Physics Roadmap", DOE Accelerator Beam Physics Roadmap Workshop, 2022.

[2] S. Antipov *et al.*, "IOTA (Integrable Optics Test Accelerator): Facility and Experimental Beam Physics Program", *JINST* 12, T03002, 2017. doi:10.1088/1748-0221/12/03/t03002

[3] A. Valishev *et al.*, "First Results of the IOTA Ring Research at Fermilab", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 19–24. doi:10.18429/JACoW-IPAC2021-MOXB02

[4] N. Kuklev, "Experimental Studies of Nonlinear Integrable Optics", PhD Thesis, The University of Chicago, 2021. doi:10.6082/uchicago.3361

[5] J. Wieland *et al.*, "Improved Measurements of Nonlinear Integrable Optics Invariants at IOTA", presented at the 14th International Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023 paper WEPL052, this conference.

[6] J. Jarvis *et al.*, “Experimental demonstration of optical stochastic cooling”, *Nature*, 608, 287-292, 2022. doi:10.1038/s41586-022-04969-7

[7] J. Jarvis *et al.*, “The Optical Stochastic Cooling Program at Fermilab”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper WEPA039, this conference.

[8] I. Lobach *et al.*, “Transverse Beam Emittance Measurement by Undulator Radiation Power Noise”, *Phys. Rev. Lett.* 126, 134802, 2021. doi:10.1103/PhysRevLett.126.134802

[9] S. Nagaitsev *et al.*, “Two-photon undulator radiation”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper MOPA170, this conference.

[10] A. Romanov *et al.*, “Experimental Single Electron 4D Tracking in IOTA”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper WEPL108, this conference.

[11] G. Stancari *et al.*, “Beam physics research with the IOTA electron lens”, *JINST* vol. 16, no.05, P05002, 2021. doi:10.1088/1748-0221/16/05/p05002

[12] S. Nagaitsev *et al.*, “Space Charge Effects and Intensity Limits of Electron-Cooled Bunched Beams”, in *Proc. PAC’95*, Dallas, TX, USA, May 1995, paper RAP22, pp. 2937–2939.

[13] A. Oeftiger *et al.*, “Simulation study of the space charge limit in heavy-ion synchrotrons”, *Phys. Rev. Accel. Beams* 25, 054402. doi:10.1103/PhysRevAccelBeams.25.054402

[14] A. Burov, “Convective Instabilities of Bunched Beams with Space Charge”, *Phys. Rev. Accel. Beams* vol. 22, no.3, 034202, 2019. doi:10.1103/PhysRevAccelBeams.22.034202

[15] O. Mohsen, R. Ainsworth, and N. Eddy, “Waker Experiments at Fermilab Recycler Ring”, in *Proc. NAPAC’22*, Albuquerque, New Mexico, USA, Aug. 2022, paper MOPA33, pp. 124.

[16] O. Mohsen *et al.*, “Investigation of transverse instabilities using a dedicated feedback system”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper WEPA014, this conference.

[17] D. Edstrom *et al.*, “IOTA Proton Injector Beamline Installation”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper TUPA183, this conference.

[18] F. Antoniou and F. Zimmermann, “Revision of Intrabeam Scattering with Non-Ultrarelativistic Corrections and Vertical Dispersion for MAD-X”, CERN-ATS-2012-066, 2012.

[19] M.K. Bossard *et al.*, “Thermionic Sources for electron cooling at IOTA”, presented at the 14th International Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023 paper MOPL046, this conference.

[20] R.C. Dhuley *et al.*, “Design of a compact, cryogen-free superconducting solenoid for the electron lens of the Fermilab Integrable Optics Test Accelerator (IOTA)”, *JINST* 16, T03009, 2021. doi:10.1088/1748-0221/16/03/T03009

[21] V. V. Parkhomchuk, “New insights in the theory of electron cooling”, *Nucl. Instrum. Meth. A* vol. 441, pp. 9–17, 2000. doi:10.1016/S0168-9002(99)01100-6

[22] A. Shishlo, S. Cousineau, J. Holmes, T. Gorlov, “The Particle Accelerator Simulation Code PyORBIT”, *Procedia Computer Science* vol. 51, pp. 1272–1281, 2015. doi:10.1016/j.procs.2015.05.312

[23] N. Banerjee, M. K. Bossard, J. A. Brandt, B. L. Cathey, Y.-K. Kim, S. Nagaitsev, and G. Stancari, “Electron Cooling With Space-Charge Dominated Proton Beams at IOTA”, in *Proc. COOL’21*, Novosibirsk, Russia, Nov. 2021, pp. 14–19. doi:10.18429/JACoW-COOL2021-S201

[24] N. Banerjee *et al.*, “Electron Cooling Experiment for Proton Beams with Intense Space-Charge in IOTA”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 2395–2398. doi:10.18429/JACoW-IPAC2022-THOXGD2