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PROPOSED LONGITUDINAL PROFILE DIAGNOSTICS FOR OPTICAL STOCHASTIC COOLING OF STORED ELECTRONS IN THE IOTA RING*

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Abstract

The Fermilab Integrable Optics Test Accelerator (IOTA) ring optical stochastic cooling (OSC) experiment is designed for a low nominal beam current (~0.1 microAmps of 100-MeV electrons) to reduce intrabeam scattering (IBS), and during cooling, OSC is expected to reduce the bunch length from ~200 ps to ~130 ps. These equilibrium bunch lengths can be measured using a streak camera and the optical synchrotron radiation (OSR) generated in a ring dipole by the circulating beam as demonstrated on a small ring elsewhere recently. The same model streak camera has been installed on IOTA, and one expects the integrated system will have sufficient sensitivity and resolution for measuring the evolution and equilibrium values of the bunch length during OSC experiments.

INTRODUCTION

Optical stochastic cooling (OSC) experiments [1] are an extension to optical frequencies of stochastic cooling experiments for particle beams performed previously in the microwave regime [2]. They are motivated by an increase in the cooling bandwidth by up to 3 orders of magnitude in principle. Complementary experiments on OSC for electrons are being implemented at 1 GeV at the Cornell Electron Storage Ring (CESR) in an arc bypass [3] and at 100 MeV at the Fermilab Integrable Optics Test Accelerator (IOTA) ring [4]. This latter experiment will use two undulators (with resonant wavelength of 0.95 µm) in a straight section of the ring for the "pickup undulator" (PU) and the "kicker undulator" (KU). An optical delay path is used to match the transit time of the photon emitted in the PU with the same electron that emitted it (after the transit of a magnetic chicane) in the KU. Small longitudinal kicks to the electrons can result in a cooling effect on the momentum offset with appropriate delay tuning.

One of the predicted signatures of successful optical stochastic cooling in the Fermilab IOTA ring is reduction of the bunch length. The IOTA OSC experiment is designed for a low nominal beam current (~0.1 microAmps of 100-MeV electrons) to reduce intrabeam scattering (IBS), and during cooling, OSC is expected to reduce the bunch length from ~200 ps to ~130 ps [4]. These equilibrium bunch lengths can be measured using a streak camera and the optical synchrotron radiation (OSR) generated in a ring dipole by the circulating beam. A similar measurement was previously performed at the Advanced Photon Source with a Hamamatsu C5680 synchroscan streak camera operating at 117.3 MHz [5]. In this case, synchronous summing of OSR resulted in a bunch length measurement of 354 ± 12 ps using only 389 electrons circulating at 425 MeV. At IOTA, an existing streak camera has been modified to operate at the 11th harmonic of the ring's revolution frequency of 7.50 MHz and has been installed on an OSR port in support of the OSC experiments. The integrated system will have sufficient sensitivity and resolution for measuring the evolution and equilibrium values of the bunch length during OSC.

EXPERIMENTAL ASPECTS

A brief description of the FAST/IOTA facility is given in this section plus that of the streak camera system being implemented to support OSC experiments.

The FAST Electron Injector Linac

The Integrable Optics Test Accelerator (IOTA) electron injector at the FAST facility (Fig. 1) begins with an L-band rf photoinjector gun built around a Cs_2Te photocathode (PC [6]). When the UV component of the drive laser, described elsewhere [7] is incident on the PC, the resulting electron bunch train with a 3-MHz micropulse repetition rate exits the gun at <5 MeV. Following a short transport section with a pair of trim dipole magnet sets, the beam passes through two superconducting rf (SCRF) capture cavities denoted CC1 and CC2, and then a transport section to the low-energy electron spectrometer. In this case this dipole is off so 25-MeV beam is transported to and through the cryomodule (CM2) with an exit energy of 100 MeV. Generally, a single bunch of ~100 pC is transported to the IOTA ring for injection into it.

The IOTA Ring

The IOTA ring is a multipurpose research accelerator which normally circulates electrons injected from the linac at 100 or 150 MeV and with a 7.50-MHz revolution frequency. Currents have been stored from a few mA to a single electron. The target area for the OSC experiments is 83,000 e^-, or 0.1 µA and lower. There are 8 dipoles in the ring lattice as shown in Fig. 2, and the streak camera was installed on the M3R OSR port. Signal is shared with one of the standard FLIR CMOS digital cameras used for e-beam transverse size measurements via OSR.

Streak Camera

A C5680 Hamamatsu streak camera with an S20 PC operating with the M5675 synchroscan vertical deflection unit will be phase locked to 82.50 MHz as shown in Fig. 3. The synchroscan unit was selected over the slow sweep unit plugin with a trigger rate of 500 kHz at 2-ns sweep and

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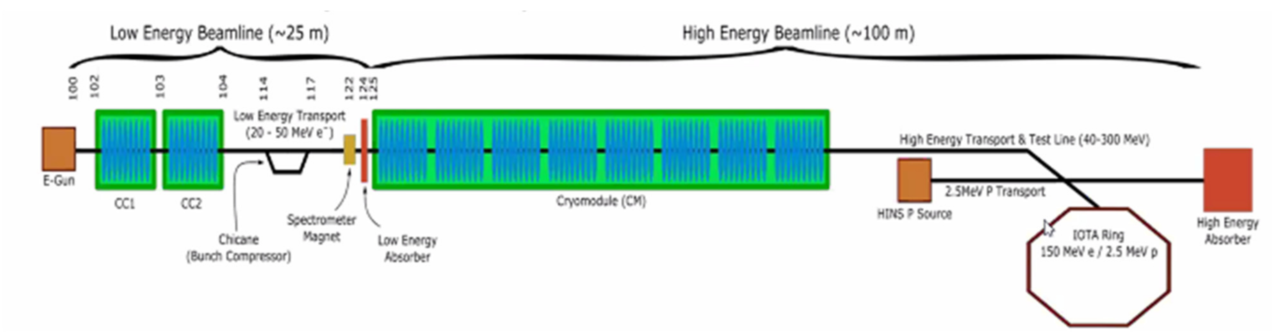

Figure 1: Schematic of the FAST linac with PC rf gun, capture cavities (CCn), low energy transport line, the cryomodule (CM), high-energy transport line, and the IOTA ring.

trigger jitter of 50 ps and the fast sweep unit with a limited trigger rate of 10 kHz compared to the 7.50-MHz revolution frequency of the IOTA ring. In addition, we use a phase-locked-loop C6878 delay box that stabilizes the streak image positions to about 1 ps temporal jitter over 10 s of minutes. These steps enable the synchronous summing of millions of OSR pulses/s generated by the circulating beam or the offline summing of 10-100 images to improve statistics in the sum images.

One can apply the principle to the OSR generated by transit of the beam through one of the IOTA dipoles, M3R. Commissioning of the streak camera system was facilitated through a suite of controls centered around ACNET. This suite includes operational drivers to control and monitor the streak camera as well as Synoptic displays to facilitate interface with the driver. Images were captured from the streak camera using the readout camera, a FLIR 1.5-Mpixel digital CMOS camera with 2/3" format. These can be analyzed both online and with an offline MATLAB-based ImageTool processing program [8]. Adjustable chip integration times 0.1-10 s will support OSR imaging at ultra-low charges. Bunch-length measurements using these techniques previously were done most relevantly on ultra-low charge at the Advanced Photon Source (APS) particle accumulator ring (PAR) [5].

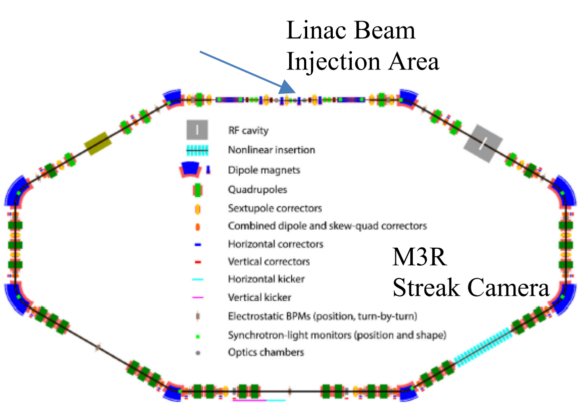

Figure 2: IOTA ring schematic showing the lattice with 8 dipoles. The M3R location for the streak camera is indicated.

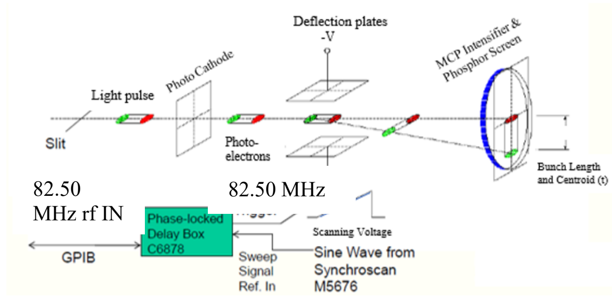

Figure 3: Schematic of the C5680 synchroscan streak camera with phase locking at 82.50 MHz.

SIMULATIONS OF THE OSC EFFECT ON THE LONGITUDINAL PROFILE

A comprehensive set of simulations that assess the IOTA OSC experiment has been provided in reference [4]. These address intrabeam scattering (IBS) as a factor in choosing a parameter space to use to minimize that competing factor in detecting the changes in transverse size due to OSC. These considerations lead to the operating target of 0.1 μA (83,000 e-) in the ring. However, the simulations also show

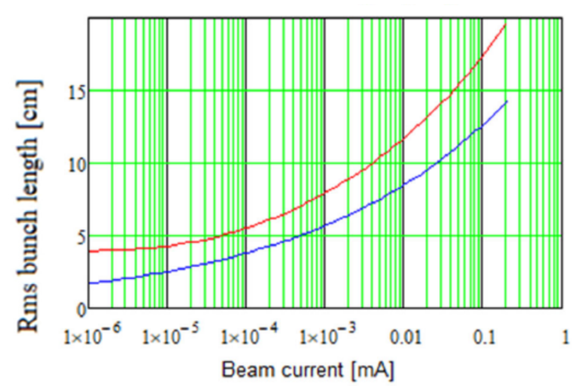

Figure 4: Dependence of rms bunch length on the beam current with (blue) and without (red) OSC [4].

that the longitudinal profile and rms bunch length should show reduction with OSC at all currents considered as shown in Fig. 4. The streak camera measurements will address these effects with potentially a temporal resolution 10 times smaller than the minimum bunch length anticipated. This will result in high sensitivity to parameter changes, more so than expected in the transverse size imaging with OSR.

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EXPERIMENTAL RESULTS

Proof-of-Principle Example at APS

An example of the x-t streak camera image from the APS PAR experiment is provided in Fig, 5 [5]. This is a 200-image sum from the camera with only 389 electrons stored. With 33 ms per frame for the 8-bit analogue camera, the sum of the digitized images was used to provide a useful image with effectively 6.6 s of integration time. The single Gaussian fit was for 354 ± 12 ps with sampling at about 10-ps resolution. This is a proof-of-principle for the application to OSC experiments starting at 83,000 e^-. With the shorter bunches anticipated in the IOTA OSC cases and with a 12-bit digital camera for readout with integration times of 1-10 s, we expect useful images to be obtainable at ultra-low charges. We note the x-t imaging could provide additional insight into the OSC process as a function of x

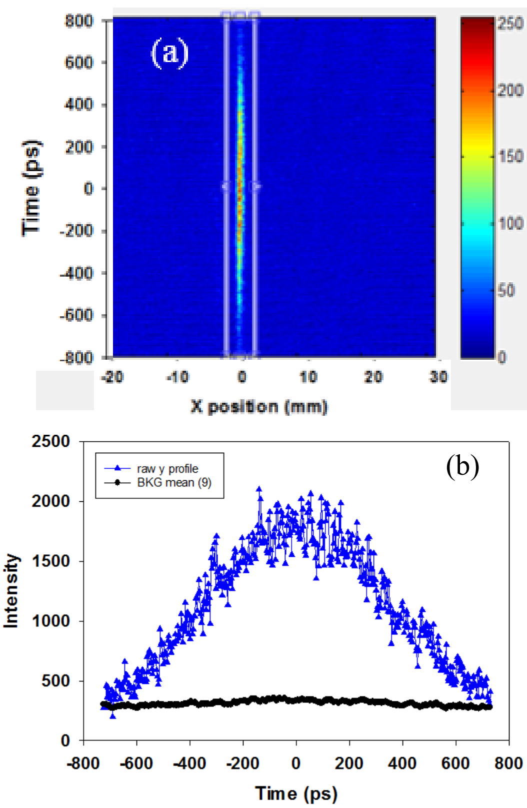

Figure 5: (a) Streak camera sum image from the APS PAR OSR source with 389 electrons stored and (b) the projected temporal profile for the image. A bunch length of 354 ± 12 ps at 425 MeV was determined with a single Gaussian fit [5].

if proper spatial imaging of the OSR source point to the streak camera entrance slit were done. Dual-sweep operations to track OSC effect evolution at the 100-ms level would be subject to statistical considerations, but successive 1-s chip integrations and 1-Hz readout should be viable at the target current. Shorter integrations would be possible at higher charges with the purpose of looking at the cooling rate of OSC [5].

Preliminary Results from IOTA

Preliminary data have recently been reported on the equilibrium bunch length at ~1 μA stored. The 20-30% reduction of bunch length with OSC cooling was visible in the comparison of the vertical/time extent of streak camera images [9].

SUMMARY

In summary, we have described a technique using a synchroscan streak camera and OSR to measure the electron-beam equilibrium longitudinal distributions in the IOTA ring as a function of stored beam current and under the OSC process. A proof-of-principle result for 389 electrons stored was shown from another small ring. An extensive set of experiments has been done with this technique to support OSC studies at IOTA in the past months which will be reported elsewhere.

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REFERENCES

[1] M. S. Zolotorev and A. A Zholents, "Transit-time method of optical stochastic cooling", *Phys. Rev. E*, vol. 50, no. 4, p. 3087, 1994.

[2] D. Moehl, G.Petrucci, L.Thorndale, and S.van der Meer, "Physics and Technique of Stochastic Cooling", *Phys. Rep.*, vol. 58, p. 73, 1980.

[3] M.B. Andorf *et al.*, "Optical Stochastic Cooling with an arc bypass in the Cornell Electron Storage Ring", *Phys. Rev. Accel. and Beams,* vol. 23, p. 102801, 2020.

[4] V. Lebedev, J. Jarvis, H. Piekarz, A. Romanov, J. Ruan, M. Andorf, "Conceptual Design Report: Optical Stochastic Cooling at IOTA", `https://arxiv.org/abs/2012.09967`

[5] A.H. Lumpkin and K. P. Wootton, "High-Resolution Longitudinal Profile Diagnostics for Ultralow Charges Stored in a Ring", *Phys. Rev. Accel. and Beams*, vol. 24, p. 072806, 2021.

[6] The ASTA User Facility Proposal, Fermilab-TM-2568, October 2013.

[7] J. Ruan, M. D. Church, D. R. Edstrom, T. R. Johnson, and J. K. Santucci, "Commission of the Drive Laser System for Advanced Superconducting Test Accelerator", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper WEPME057, pp. 3061-3063.

[8] R. Thurman-Keup, FNAL, off-line MATLAB-based Image-Tool, 2011.

[9] Jonathan Jarvis and Valeri Lebedev, "OSC at IOTA: The World's First Experimental Demonstration of Optical Stochastic Cooling", Accelerator Physics and Technology Seminar, May 11, 2021, Fermilab.