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SYNCHROTRON RADIATION BEAM DIAGNOSTICS AT IOTA - COMMISSIONING PERFORMANCE AND UPGRADE EFFORTS*

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Abstract

The Integrable Optics Test Accelerator is a research electron and proton storage ring recently commissioned at the Fermilab Accelerator Science and Technology facility. A key part of its beam diagnostics suite are synchrotron radiation monitors, used for measuring transverse beam profile, position, and intensity. In this paper, we report on the performance and uses of this system during the year 1 run. We demonstrate sub-100nm statistical beam position uncertainty and high dynamic range from 10^9 electrons down to a single electron. Commissioning challenges and operational issues are discussed. We conclude by outlining current upgrade efforts, including improved modularity, small emittance measurements, and a multi-anode photomultiplier system for turn-by-turn acquisition.

INTRODUCTION

Integrable Optics Test Accelerator (IOTA) is a new research electron and proton storage ring located at Fermilab's Accelerator Science and Technology (FAST) facility that just completed its first year commissioning and scientific run. It has a circumference of 40m, and is designed to use either 2.5 MeV protons provided by an RFQ injector, or up to 150 MeV (100 MeV this run) electrons from FAST linac [1]. Over next few years, a comprehensive experimental campaign is planned including tests of techniques for improving beam intensity and stability (with integrable optics [2–4], and electron lenses [5]), a demonstration of optical stochastic cooling [6], single electron quantum optics and undulator radiation studies [7], advanced beam diagnostics development [8], and others. All of these project either directly or indirectly require accurate beam intensity and transverse profile measurements, which will be provided by the Synchrotron Radiation (SR) diagnostics suite, called SyncLight (SL) [9]. This paper provides an overview of the SL system, its uses during the run, and planned upgrades.

Background and System Overview

Synchrotron radiation is produced by charged particles undergoing radial acceleration, and is a byproduct in any storage ring. It plays a large role in beam damping, and is also a commonly used diagnostic signal [10, 11]. SR intensity profile is strongly forward peaked, with total radiation power scaling as fourth power of particle energy. For IOTA, protons do not produce sufficiently intense or energetic SR signal, but for electrons, critical wavelength is in the UV range, allowing for simple and cost effective measurements with silicon-based sensors and visible band optics.

IOTA ring contains 8 bending dipole magnets, with 4 each of 30 and 60 degree varieties. All the vacuum chambers have downstream optically transparent windows, through which SR can be extracted. A schematic diagram of the IOTA ring is shown in Fig. 1 - note that in 4 of 8 sections, radiation from potential insertion devices in the straights can also be observed.

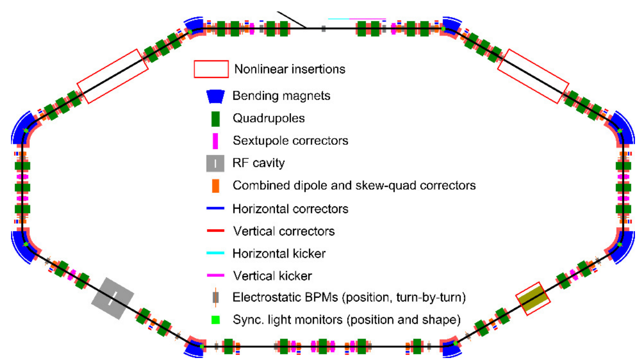

Figure 1: Layout of IOTA ring, with injection point in the upper central section. Main bends are in blue.

SyncLight system is comprised of 8 stations situated atop each of the dipoles. In base configuration, each station has two components - first is an optical periscope transport line consisting of two mirrors, an iris, and a lens, that captures SR and focuses it onto the detector, while using the iris to limit depth of field errors. Second and more extensive part is the modular detector station, that in its base configuration contains a low-noise CMOS camera, but also provides capability to add modules like color wheels, photomultipliers (PMTs), polarizers, and other devices. It houses various connectivity and support electronics, including Raspberry Pi motor control nodes and fanouts for add-on connectivity - power, Ethernet, shielded high voltage and heliax signal cables. All key components are motorized, allowing for remote alignment and changes to the optical configuration. Main camera detector is read out at 10FPS to a DAQ server cluster, which processes the images in real time to extract beam intensity, position, and size, and forwards that information with compressed data onto user consoles and the general accelerator controls network. We are in the process of open-sourcing the software framework, since it is highly modular and easily adaptable to other facilities. A typical station configuration is shown in Fig. 2.

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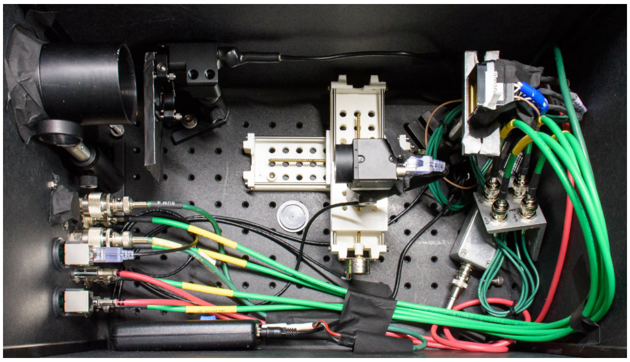

Figure 2: SL station with PMT addon module installed.

COMMISSIONING AND STUDIES

SyncLight system was used extensively during all stages of the year 1 run, from measuring initial closed orbits (where it could see lower currents than the button BPM system), to the final lattice optics correction (where its resolution, linearity, and noise characteristics provided best constraints for the LOCO [12–14] algorithm), to collecting key data for several of the experiments. The performance of the system was evaluated and improved continuously throughout the run - for instance, slight changes in RF (and hence orbit length) were used to calibrate the system magnification, and few-electron images were used to get an absolute intensity calibration. Direct evaluation of some parameters, like position resolution, was made difficult due to systematic beam drifts - for near Gaussian beams and short time intervals, we observed statistical position errors below 100 nm, several orders of magnitude lower than drift amplitudes. In the following subsections, we highlight some of the experiments that made use of the SL system and discuss the relevant performance parameters.

Intra-beam Scattering and Lifetime

Intra-beam scattering (IBS) is a phenomenon caused by particles scattering within the bunch, which transfers momentum between the longitudinal and transverse degrees of freedom. For lepton storage rings, this corresponds to an effective increase in equilibrium emittance. In IOTA, IBS is undesirable since it negatively affects measurements, such as that of dynamic aperture for nonlinear optics. Unfortunately, limited BPM system dynamic range necessitates at least 1mA of current for many measurements, at which point IBS is still significant. To better understand and correct for this, SL system was used in combination with wall current monitor to measure beam size and lifetime as function of current, from which fitted IBS model parameters were derived. Beam size changes with current for a typical injection are shown in Fig. 3, along with Completely Integrated Modified Piwinski (CIMP) model fits. Notably, the full dynamic range of this measurement was covered by only a single optics configuration with an ND=2.0 filter addon.

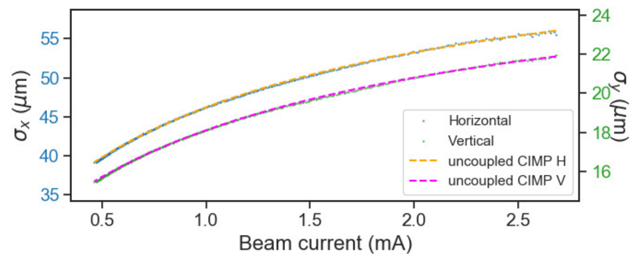

Figure 3: Dependence of 1 σ beam sizes on current for near-round beam, in minimally coupled lattice.

Single Electron Detection

The quantum nature of electron SR emission is often masked by the large number of particles in the ring. However, there are a number of interesting phenomena that can only be observed at ultra-low, few to single electron currents. Typically, such ranges require using PMTs, which sadly do not provide any spatial information. However, with low-noise cameras it is possible to integrate the signal for millions of turns (hundreds of ms) and obtain both intensity and spatial information. Once post-processed to remove hot pixels and background, sum signals from cameras were sufficient to discriminate (Fig. 4) the number of electrons quickly and with high accuracy, cross-checking the initial PMT observations. Unfortunately, long integration times smear out a lot of the intricate behavior, like gas scattering events - our efforts to solve this will be discussed below.

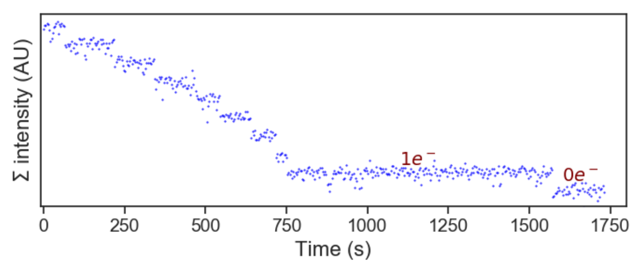

Figure 4: Post-processed sum of pixel intensities for a single camera, showing discrete steps as electrons are lost.

Emittance Measurements

One of planned IOTA configurations will have beam sizes too low to image directly with sufficient resolution. However, a simple polarizer and bandpass filter module can be inserted to remove σ-mode radiation, and use remaining π-mode (which has a significantly more diffuse and weaker signal) to fit an emittance model with high accuracy. To test the feasibility of this add-on, a polarizer rotation scan was performed in a low emittance configuration, with resulting best profile (shown in Fig. 5) having the expected two-peak distribution with a well resolved central dip.

Nonlinear Optics

Due to the various imperfections and nonlinearities in the lattice, beam shape can become strongly non-Gaussian,

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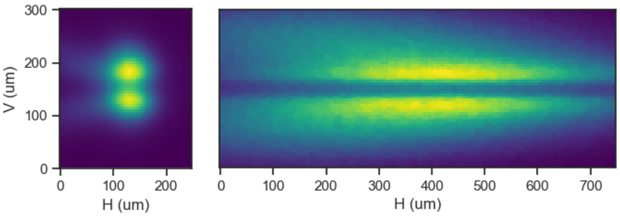

Figure 5: An optimally resolved π mode image in low-emittance (left) and nonlinear optics (right) configurations.

which introduces a bias for averaging systems like BPMs. One such case is for studies of octupole-based nonlinear integrable optics inserts near 1/4 resonance, whereupon stable but high amplitude orbits were observed, as shown in Fig. 6. These phenomena were not initially expected, and have stimulated efforts to reproduce and understand their origin in tracking simulations.

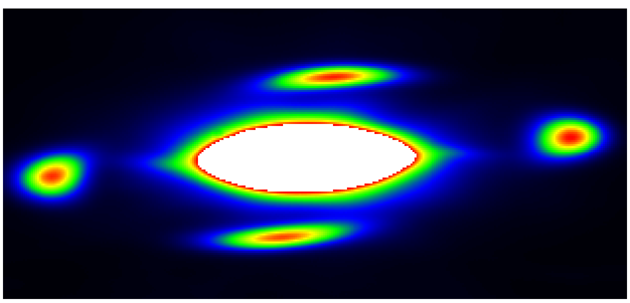

Figure 6: Transverse beam profile after injection near 1/4 resonance with nonlinear octupole insert on. Black denotes no signal, and white a complete saturation.

PLANNED UPGRADES

While highly effective, one disadvantage of SL system modularity was significant downtime due to constant hardware modifications, so as to carer to specific experimental requirements. For year 2, further optomechanics additions are planned, such as selectable beam splitters, which will allow for several optical 'beam lines' to be served simultaneously and independently at each station, with minimal need to disturb the main camera. Extensive use of 3d-printed parts and custom controllers will allow for significant cost savings as compared to commercial solutions.

Other desired improvements, as mentioned previously, will focus on sensitivity and time resolution. Unfortunately, buying better cameras will not be sufficient due to fundamental sensor limits - achieving significant improvements requires another type of detector. As such, we are developing a multi-anode PMT prototype, where each anode will effectively serve as a 'pixel' of a camera, but with turn-by-turn resolution and single-electron sensitivity. Currently, several vendors offer 8x8 detectors, and we have successfully tested a 4x4 variant during this run. There are two main implementation challenges - first is the optical tracking system that can optimize PMT coverage (and thereby spatial resolution) for all the possible lattice configurations. This is a straightforward extension of our previous automation work, but requires careful design and testing due to tradeoffs in resolution, sensitivity, and cost. Second challenge is a cost effective and fast multi GS/s readout - for IOTA bunch length (10 cm), revolution period (133 ns) and typical pulse FWHM (5-10 ns, <1 ns rise time), there is little room to multiplex signals, but acquiring a commercial 64 channel simultaneous ADC is prohibitively expensive. We are exploring fast selectable multiplexing schemes (reading out only most relevant 'pixels') and repurposing spare particle detector digitizer boards as possible solutions.

CONCLUSION

We have presented the summary of year 1 architecture, commissioning, and uses of the IOTA SyncLight beam diagnostics suite. The system has met most of its design goals, achieving superb spatial resolution and sensitivity, and has been successfully used for a number of experiments. Operationally, we found that a modular design based on cheap, commercially available electronics allowed for rapid changes to suit experimental needs, at the cost of downtime required to restore the base configuration. We are planning a number of upgrades, including further automation and multi-pixel PMT detectors, to extend the capabilities for year 2 run, expected to begin in the fall of 2019.

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