Notes on the design of experiments and beam diagnostics with synchrotron light detected by a gated photomultiplier for the Fermilab superconducting electron linac and for the Integrable Optics Test Accelerator (IOTA)

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We outline the design of beam experiments for the electron linac at the Fermilab Accelerator Science and Technology (FAST) facility and for the Integrable Optics Test Accelerator (IOTA), based on synchrotron light emitted by the electrons in bend dipoles, detected with gated microchannel-plate photomultipliers (MCP-PMTs). The system can be used both for beam diagnostics (e.g., beam intensity with full dynamic range, turn-by-turn beam vibrations, etc.) and for scientific experiments, such as the direct observation of the time structure of the radiation emitted by single electrons in a storage ring. The similarity between photon pulses and spectrum at the downstream end of the electron linac and in the IOTA ring allows one to test the apparatus during commissioning of the linac.

I. INTRODUCTION

Synchrotron radiation has been widely used as non-destructive beam diagnostic [1]. We propose to use a gated photomultiplier to collect synchrotron light generated by the beam in bending dipoles, both at the downstream end of the electron linac of the Fermilab Accelerator Science and Technology (FAST) facility and in the Integrable Optics Test Accelerator (IOTA).

The goals include both advanced beam diagnostics and scientific experiments. The main objectives are the following:

- Characterize synchrotron-light signal and backgrounds in these specific accelerator environments;

- Develop a bunch-by-bunch (for the linac) or turn-by-turn (for IOTA) intensity monitor with a wide dynamic range, from nominal intensities down to single electrons;

- Record turn-by-turn beam vibrations in IOTA with high sensitivity, for experiments in beam dynamics;

- Directly observe the time structure of radiation emission from a single electron in a storage ring.

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II. BEAM PULSE STRUCTURE

The linac bunches have an intensity of $3 \times 10^7$ particles (5 pC) to $2 \times 10^{10}$ (3 nC), a pulse width of the order of picoseconds, and a spacing of 333 ns (111 ns may also be possible). The pulse train can contain between 1 and 3000 bunches (1 ms maximum pulse width), with a repetition rate of 1 Hz.

IOTA will circulate single nominal bunches of $2 \times 10^9$ electrons, with a revolution period of 133 ns. The rms bunch length will be 0.4 ns. Intensities can be lowered down to single electrons in a controlled way by manipulating the orbit, lattice or radiofrequency voltage.

Linac and IOTA beams will have similar pulse structures. In both cases, the bunch length is short compared to the time resolution of a typical photomultiplier, so that photon signals within a bunch overlap in the detector output.

III. EXPECTED SIGNAL

Synchrotron light is emitted by electrons in bending dipoles, collected through a window in the straight-through section of beam pipe, transported through lenses and mirrors, and collected by a photomultiplier positioned on top of the dipole magnet.

We calculate the expected number of photoelectrons per electron per pass using classical synchrotron radiation formulas for long magnets [1], the transmission of the optical components, and the spectral response of the photomultiplier.

The layout of the accelerator is described in detail in Ref. [2]. A few cases with different energies are chosen (Table I), both for the D600 15-degree dipole at the downstream end of the 300-MeV beam line of the electron linac and the 30- and 60-degree dipoles in IOTA (150-MeV nominal electron energy).

The spectral photon fluxes are shown in Figure 1 for different cases. With the appropriate choice

<p>| Table I. Chosen experimental cases and typical synchrotron-light parameters. |
|----------------------------------------|--------|---------|--------|--------|--------|--------|--------|--------|</p>
<table>
<thead>
<tr>
<th>Lorentz factor $\gamma$</th>
<th>Radius $\rho$ [m]</th>
<th>Critical freq. $\omega_0$ [$10^{15}$ rad/s]</th>
<th>Critical energy $E_N$ [eV]</th>
<th>Power $P_s$ [nW]</th>
<th>Energy loss $U_s$ [eV/turn]</th>
<th>$n_s$ [/turn]</th>
<th>Full cone $\phi$ [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D600 300 MeV</td>
<td>587</td>
<td>4.89</td>
<td>18.6</td>
<td>12.2</td>
<td>0.229</td>
<td>147</td>
<td>38.9</td>
</tr>
<tr>
<td>D600 200 MeV</td>
<td>391</td>
<td>4.89</td>
<td>5.51</td>
<td>3.63</td>
<td>0.0452</td>
<td>28.9</td>
<td>25.9</td>
</tr>
<tr>
<td>D600 150 MeV</td>
<td>294</td>
<td>4.89</td>
<td>2.33</td>
<td>1.53</td>
<td>0.0143</td>
<td>9.16</td>
<td>19.4</td>
</tr>
<tr>
<td>D600 100 MeV</td>
<td>196</td>
<td>4.89</td>
<td>0.689</td>
<td>0.454</td>
<td>0.00283</td>
<td>1.81</td>
<td>13</td>
</tr>
<tr>
<td>IOTA 150 MeV</td>
<td>294</td>
<td>0.7</td>
<td>16.2</td>
<td>10.7</td>
<td>0.699</td>
<td>64</td>
<td>19.4</td>
</tr>
<tr>
<td>IOTA 100 MeV</td>
<td>196</td>
<td>0.7</td>
<td>4.81</td>
<td>3.17</td>
<td>0.138</td>
<td>12.6</td>
<td>13</td>
</tr>
</tbody>
</table>
Figure 1. Spectral flux density of synchrotron-light photons (top); transmission of light-transport system (middle); quantum efficiency of photodetector (bottom).
of beam energy, spectra and fluxes at the D600 dipole can be made remarkably similar to those expected at the IOTA dipoles.

The light transport system is assumed to collect the full synchrotron-radiation cone. It includes a 6-mm-thick crystalline quartz window, 4 UV-enhanced aluminum mirrors, and a fused silica lens with UV antireflective coating. The transmission of each individual element (from the manufacturer) and the total transmission are shown in Figure 1 (middle plot) as a function of photon energy and wavelength.

The quantum efficiency of the photodetectors is also shown in Figure 1 (bottom plot). Two curves are drawn: one for the existing MCP-PMT from the Tevatron Synclite system [3] (Hamamatsu R5916U-50 mod. 2) and one for a commercial infrared-enhanced device (Hamamatsu R3809U-51). (Although its infrared response is enhanced, the loss of quantum efficiency over the rest of the spectrum yields a lower overall signal.)

The average number of photons per electron per pass is obtained by multiplying the quantum efficiency, averaged over the emission and transmission spectra, by the total number of photons per pass. The results are shown in Table II.

For a single electron circulating in IOTA (revolution period \(T_{\text{rev}} = 133\) ns, revolution frequency \(f_{\text{rev}} = 7.52\) MHz), we expect an average counting rate of 1.4 kHz, with a negligible probability of 2 photons being emitted in the same dipole. A small number of circulating electrons, and discrete steps in counting rates due to losses of electrons, should be clearly detectable with counting times of the order of 1 s. For nominal IOTA intensities, the analog output of the photomultiplier can be integrated to provide a signal proportional to the beam current. Reading out the photomultiplier signal in both counting and current mode allows one to cover the full dynamic range, from 1 electron to nominal bunches.

For preliminary experiments at the D600 dipole, one can test the current readout mode with nominal IOTA bunches (300 pC) and the counting mode with low-intensity bunches (e.g., 3 pC) and a neutral density filter to suppress multiple photons from the same bunch.

<table>
<thead>
<tr>
<th></th>
<th>Avg. Q.E. ([10^{-3}])</th>
<th>Error on avg. Q.E. ([10^{-5}])</th>
<th>Average number of collected photoelectrons (N_{pe} \times 10^{-4}/e^-/pass)</th>
<th>Integration error on (N_{pe} \times 10^{-6}/e^-/pass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D600 300 MeV</td>
<td>8.72</td>
<td>1.5</td>
<td>1.84</td>
<td>0.315</td>
</tr>
<tr>
<td>D600 200 MeV</td>
<td>6.89</td>
<td>1.57</td>
<td>1.45</td>
<td>0.33</td>
</tr>
<tr>
<td>D600 150 MeV</td>
<td>3.07</td>
<td>2.49</td>
<td>0.647</td>
<td>0.525</td>
</tr>
<tr>
<td>D600 100 MeV</td>
<td>0.108</td>
<td>1.37</td>
<td>0.0228</td>
<td>0.289</td>
</tr>
<tr>
<td>IOTA 150 MeV</td>
<td>8.74</td>
<td>1.53</td>
<td>1.84</td>
<td>0.321</td>
</tr>
<tr>
<td>IOTA 100 MeV</td>
<td>6.38</td>
<td>1.53</td>
<td>1.34</td>
<td>0.323</td>
</tr>
</tbody>
</table>
A continuously variable neutral-density filter with high gradient can be used to translate beam displacements into intensity modulation of synchrotron light. Similar experiments were done in the past using a hard-edge screen [4], but beam alignment was time-consuming. The variable neutral density filter should be less sensitive to beam alignment, at the cost of a poorer spatial sensitivity.

The ability to store and monitor single electrons in IOTA opens up several research areas [5–9]. One of them is the study of the physics of synchrotron radiation and its effect on the dynamics of single particles. In particular, we are interested in the direct observation of the time series of photon emissions of a single particle in a storage ring: is it random, chaotic, or regular? This study can be started with the initial IOTA configuration, and enhanced at a later stage by the insertion of an undulator (a possible synergy with the optical stochastic cooling experiments).

IV. BACKGROUNDS AND SYSTEMATIC EFFECTS

One of the main purposes of preliminary studies at the D600 dipole location is to assess background levels and their fluctuations. Typical background and noise sources include thermionic emission, radiation (natural or accelerator-induced), afterpulsing, and light leaks.

A gated photodetector provides strong background reduction. Another technique we will investigate is a lengthening of the synchrotron-radiation path in order to delay the signal pulse with respect to the arrival of the beam.

The effect of the magnetic field on the photomultiplier response needs to be investigated as well.

V. APPARATUS

A. Light collection and transport

The light transport system is designed to collect the full synchrotron-radiation cone emitted in the body of the dipole magnet (D600 in the linac, 30-deg or 60-deg in IOTA).

Radiation emitted by the electron beam in the dipole leaves the vacuum chamber through a 6-mm-thick crystalline quartz window. Transport and focusing is provided by 4 UV-enhanced aluminum mirrors and a fused silica lens with UV antireflective coating. A variable neutral-density filter controls the intensity of the transmitted light. The microchannel-plate photomultiplier (Hamamatsu R5916U-50 mod. 2) is placed in a dark box on top of the dipole magnet, together with other diagnostics, such as the synchrotron-radiation cameras for beam position and size measurement.
B. Data acquisition

The data-acquisition system (Figure 2) is located in the Electrical Service Building (ESB) above the IOTA enclosure.

The signal from the photomultiplier is split into 3 readout chains: 1 analog for pulse-height analysis and 2 digital for counting and timing.

The analog chain consists of a gated fast bunch integrator (similar to the ones used in the Tevatron and Main Injector). Individual pulses are integrated over a time window and read out via VMEbus into ACNET devices.

The digital chains start with a constant-fraction discriminator. The signal is then sent to counters (a visual scaler for local readout and a Struck SIS-3805 VME scaler) and to a time-to-digital converter (TDC). The counting rates are available via ACNET devices.

The time-to-digital conversion is under development. It is designed to store the time difference between the beam synchronization signal (laser pulse in the linac, radiofrequency reference in IOTA) and the synchrotron radiation signal for a given number of turns (for IOTA) or microbunches

![Figure 2. Schematic diagram of the data-acquisition system.](image-url)
VI. CONCLUSIONS

We present the design of a detection system for synchrotron radiation with gated photomultipliers in the Fermilab Integrable Optics Test Accelerator and electron linac for a set of beam energies. The system can be used for both diagnostics and physics experiments.

The time structure of the beam and the spectral photon fluxes at the downstream end of the linac and in the IOTA bending dipoles are similar. This allows one to set up and study the system during linac commissioning as IOTA is being constructed. Taking into account beam energy, dipole bend radius, transmission of the optical system, and quantum efficiency of the photodetector, the average photoelectron yield for a typical case (IOTA 150 MeV) is $1.8 \times 10^{-4}$ for each electron in the beam per pass in a dipole magnet (Table II). As a consequence, if background levels are low (or if their fluctuations are small) compared to the signal, intensities and losses of individual electrons should be detectable in IOTA with integration times of the order of a second.

The addition of precise signal timing with state-of-the-art accuracy (< 10 ps) [10] would be highly valuable to enable direct observation of the time structure of synchrotron radiation emission from single particles in a storage ring.

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[5] F. Riehle et al., “Determination of electron currents below 1 nA in the storage ring BESSY by measure-


[10] J. Christiansen, CERN HPTDC (commercially available) and picoTDC boards (private communication).