FIRST RESULTS FROM COMMISSIONING THE REAL-TIME INTERFEROMETER AS A BUNCH-LENGTH MONITOR FOR SUB-MM ELECTRON BUNCHES

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Abstract

Single-shot, non-invasive bunch length measurement of sub-mm electron bunches is attractive for future high intensity accelerators. A real-time interferometer (RTI) has been developed and commissioned for the first time to monitor the bunch length of an electron beam in an accelerator. The RTI employs spatial autocorrelation, reflective optics, and a fast response pyro-detector array to obtain a real-time autocorrelation trace of the FIR coherent radiation from an electron beam thus providing the possibility of online bunch length diagnostics. A complete RTI system has been commissioned at the A0 photoinjector facility to measure sub-mm bunches at 13 MeV using coherent transition radiation. Bunch length variation (FWHM) between 0.8 ps to 1.5 ps has been measured. Bunch length estimates extracted from interferograms are directly compared to those from a Martin-Puplett interferometer and a streak camera. The results show that the RTI is a viable, portable and complementary bunch length diagnostic for sub-mm electron bunches that could be readily deployed at an advanced accelerator electron beam facility.

INTRODUCTION

Interferometers are routinely used in accelerators to measure the autocorrelation of the beam-emitted radiation, which contains the bunch-length information. A major drawback of using a scanning interferometer is that it takes several minutes to scan one mirror to record an autocorrelation trace and involves multiple shots. The Real-Time Interferometer (RTI) was designed and developed to operate in single-shot mode and can record the autocorrelation trace in real-time[1]. We present the first results from commissioning the RTI at the Fermilab A0 photoinjector (A0PI) and provide direct comparison to results from a scanning interferometer as well as a streak camera. The RTI constructs the autocorrelation of the coherent transition radiation (CTR). The RTI measurements can be made non-invasive by using a different coherent source such as coherent synchrotron radiation, coherent edge radiation, etc.

The commissioning of the RTI can be found in [2]. In this paper, we briefly describe the commissioning results and explain the difference in bunch length measured by the streak camera and the RTI by calculating the RTI low-frequency loss at longer bunch lengths.

THE REAL-TIME INTERFEROMETER

The RTI relies on the spatial autocorrelation of a split signal where the two beams recombine on the plane of a detector array at a small angle. This differs from the standard interferometer, where the two beams are split and recombined after introducing a time delay (path length difference) to one of the beams.

Diagnostic Layout

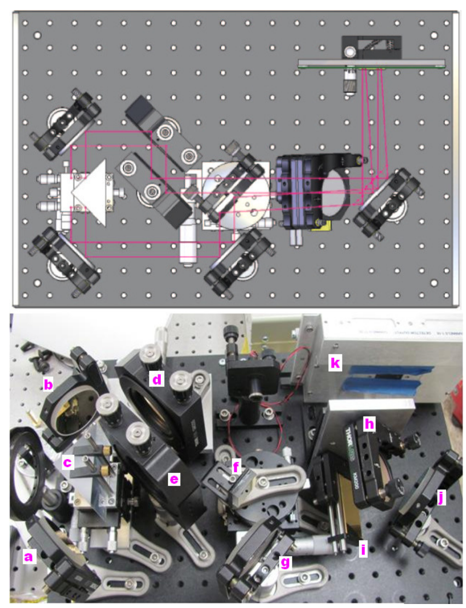

Figure 1: The top figure shows the engineering design of the RTI with the optics. The lines trace the rays of the radiation through the optics. The bottom figure shows the actual experimental setup of the RTI.

The RTI shown in Fig. 1 employs reflective optics due to the low power levels and frequency range of the emitted radiation. Because CTR is radially polarized, a wire-grid polarizer is used to select the vertical component. The radiation is then sent to the interferometer where it meets a wedge splitter and gets separated into two lobes. After the two lobes travel through equal path lengths, the pulses are

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recombined at a small angle at the cylindrical mirror. Finally, the cylindrical mirror focuses the beams in one dimension to create a line focus at the pyrodetector at the set angle. The angle of overlap between the two lobes is controlled by a small mirror mounted on an 'angle-adjustable' mount. The angle of overlap determines the path length difference between the pulses necessary for the interferometry. Further details about the RTI with preliminary laboratory results are mentioned elsewhere[1].

The Pyrodetector

The RTI detector array contains 32 elements. Each element is 500 μm by 1 mm and consists of a monolithic, 25 μm thick $LiTaO_3$ crystal coated with chromium to increase the sensitivity in the 0.2-3.0 THz range. The detector channels are set up with a RC time constant of $\sim$100 μs; the rise time is less than 10 μs. The lowest range that could be set at full scale was 2 nJ, with a maximum of 2 μJ. The readout of all 32 channels requires 5 msec (or 150 μs per channel).

EXPERIMENTAL SETUP

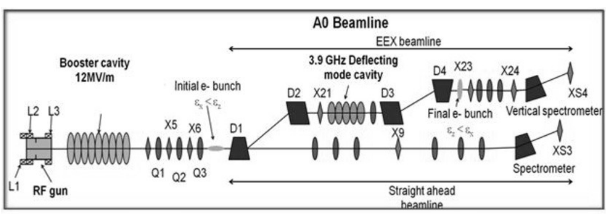

Figure 2: Experimental setup of the A0 photoinjector facility. The electrons generated by the RF gun are accelerated by the booster cavity to 14 MeV. The beam is then focused using quadrupoles (Q1,Q2,Q3) before it is sent through the EEX beam line. After going through the dogleg section of the beamline, the beam hits a metal screen at X24 and generates Coherent Transition Radiation (CTR) which is transported to the RTI. The quadrupoles are marked as ovals and the diagnostic stations are marked as diamonds. D1, D2, D3 and D4 are dipole magnets used to bend the beam.

The RTI was installed and tested at the A0PI photoinjector facility which is shown in Fig. 2. One of the experimental goals of the A0PI facility is to test and develop the concept of emittance exchange (EEX) in which the transverse phase space of the electron beam is exchanged with its longitudinal phase space[3]. To observe the emittance exchange, the bunch length, among other beam parameters, has to be measured before and after the EEX process. Currently a Hamamatsu C5680 streak camera, Martin-Puplett interferometer, and helium-cooled bolometer are available to measure the bunch length of the electron beam at X24. Typically, the bunch length is measured via the autocorrelation of the CTR transmitted through a single-crystal diamond window as the beam hits an aluminum screen. The CTR radiation is then sent either to the Martin-Puplett interferometer or the RTI.

EXPERIMENTAL RESULTS

The autocorrelation trace was measured under the following experimental conditions: The beam charge was 180 pC and the electron beam energy was 13.4 MeV. The mixing angle initially was set to $\sim$5.3 $^\circ$. There were 40 micropulses in the pulse train at 1 MHz with a repetition rate of 1 Hz. After the RTI measurement, a Martin-Puplett interferometer was used to measure the autocorrelation of the CTR from X24.

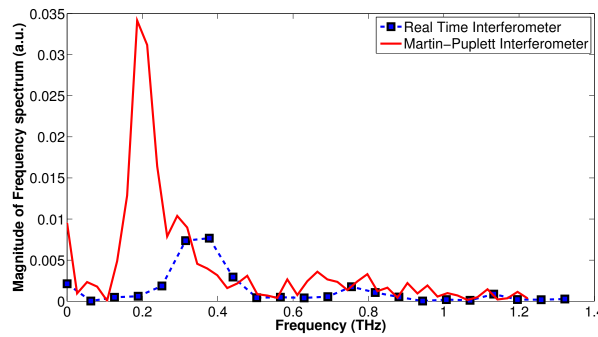

Figure 3: Fast Fourier Transform of the autocorrelation trace obtained from the RTI and MPI. The difference in the size of the detector might explain the low frequency response.

Although the RTI has only 32 channels, by remotely moving one of the mirrors (mirror d in Fig. 1), a complete autocorrelation can be determined. We moved the mirror in steps of 0.4 mm to obtain several traces and then combined them together to generate the autocorrelation. The Fourier transform of the autocorrelation trace are shown in Fig. 3.

Next, the RTI was used to measure bunch lengths for different quadrupole settings using EEX, and the results were compared with the streak-camera results. The bunch length is estimated as follows: first, the discrete autocorrelation signal is converted to a continuous trace by fitting a Gaussian curve through the center of each pixel element. The FWHM of the spatial autocorrelation trace is then calculated from the Gaussian fit. The temporal FWHM of the signal is determined by a simple formula: $t_{FWHM} = \frac{N sin(\theta)\delta x}{Kc}$, where θ is the mixing angle, δx = 500 μm, c is the speed of light, N is the FWHM of the autocorrelation trace and K is a factor depending on the shape of the pulse. For our analysis we assumed a Gaussian beam profile for which K is 1.414.

The streak camera at the A0PI was operated in synchroscan mode in which all the micropulses are synchronously summed and include slew and jitter effects. The streak camera data were taken with the synchronous sum of 60 bunches, and averaged over 25 shots. The statistical uncertainty is a much smaller contribution than the esti-

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mated 10% uncertainty in the chromatic bandwidth correction term for the system[4].

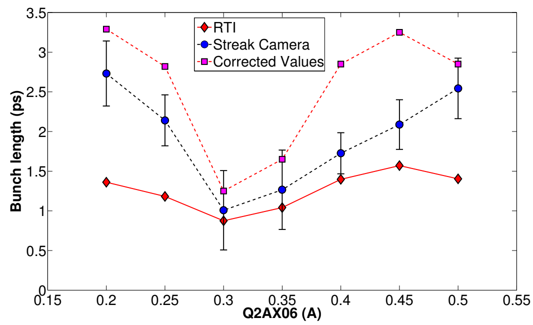

Figure 4: A comparison of the bunch length (FWHM) obtained from the streak camera and the RTI for various quadrupole settings of Q3, which changes the bunch length at X24 due to emittance exchange. The figure shows the corrected values obtained using Fig. 5.

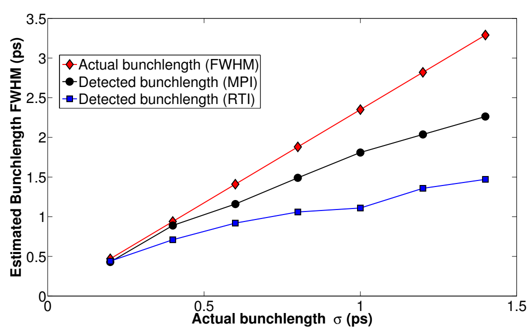

Figure 5: Calculated bunch length versus actual bunch length by taking into account the measured low-frequency cut-off of the detector.

Comparison with a Streak Camera

The RTI measurements were compared to bunch length measurements from the streak camera. There is a good agreement between the RTI and the streak camera for bunch lengths (FWHM) less than 1.0 ps as shown in Fig. 4. At longer bunch lengths, the discrepancy between the two techniques becomes large due to the low frequency response of the RTI detector. However, for shorter bunches this effect would be reduced - a trend that works to our advantage for using RTI as a bunch-length monitor for electron bunch length in the sub-ps regime.

In order to investigate the difference in the bunch length measurements reported by the streak camera and the RTI, a simplified model was used. The program[5] calculates the autocorrelation of a Gaussian signal including selectable high- and low-frequency cutoffs. In our experiment, the high-frequency cut-off is determined by the diamond window and is less than 10μm and is negligible for A0[6, 7]. The low frequency cut-off as mentioned before is determined by the imaging optics and detector aperture. Though an accurate value of the low-frequency cut-off is lacking, this number can be estimated for both the RTI and the MPI from the power spectra shown in Fig. 3. The RTI has a low-frequency cut-off at 0.25 THz and the MPI at around 0.1 THz. By using these numbers, we obtained an estimate for the actual bunch length measured by both the MPI and the RTI for a set of inital bunch lengths. This is shown in Fig. 5 and this calculation is applied to our data and is shown in Fig. 4. This simple estimation of the bunch length from the autocorrelation central peak excludes the form factor or the shape of the bunch, which could play a significant role. Moreover, the program has a continuous roll-off near the cut-off frequency while the detector will have discrete frequency characteristics. Similar behavior has been observed between the Martin-Puplett interferometer and the streak camera.

CONCLUSION AND FUTURE WORK

The real-time interferometer (RTI) has been commissioned at the A0 photoinjector. For the first time, the autocorrelation was promptly recorded in real-time as compared to several minutes for the Martin-Puplett interferometer. It has sensitivity to the variation in bunch length of the electron beam in the sub-mm regime. As our calculation and measurements indicate, the limitations of the RTI posed by the low-frequency behaviour does not prevent RTI from measuring sub-ps and femtosecond bunches. Further techniques on improving both the design of the RTI and the accuracy of the measurement are being pursued.

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