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Synchroscan streak camera imaging at a 15-MeV photoinjector with emittance exchange[☆]

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ABSTRACT

At the Fermilab A0 photoinjector facility, bunch-length measurements of the laser micropulse and the e-beam micropulse have been done in the past with a fast single-sweep module of the Hamamatsu C5680 streak camera with an intrinsic shot-to-shot trigger jitter of 10–20 ps. We have upgraded the camera system with the synchroscan module tuned to 81.25 MHz to provide synchronous summing capability with less than 1.5 ps FWHM trigger jitter and a phase-locked delay box to provide phase stability of ~1 ps over 10 s of minutes. These steps allowed us to measure both the UV laser pulse train at 263 nm and the e-beam via optical transition radiation (OTR). Due to the low electron beam energies and OTR signals, we typically summed over 50 micropulses with 0.25–1 nC per micropulse. The phase-locked delay box allowed us to assess chromatic temporal effects and instigated another upgrade to an all-mirror input optics barrel. In addition, we added a slow sweep horizontal deflection plug-in unit to provide dual-sweep capability for the streak camera. We report on a series of measurements made during the commissioning of these upgrades including bunch-length and phase effects using the emittance exchange beamline and simultaneous imaging of a UV drive laser component, OTR, and the 800 nm diagnostics laser.

1. Introduction

In analogy to upgrades performed two decades ago in support of rf linac driven free-electron lasers [1], the opportunity for a new series of streak camera experiments at the Fermilab A0 photoinjector (A0PI) on the 14–16 MeV electron beams and the UV component of the drive laser has been identified and now realized. These bunch-length and phase-stability measurements were driven by the need to diagnose accurately the beam's longitudinal emittance for the ongoing emittance exchange (EEX) studies at the facility [2–4]. The enabling upgrade was adding the synchroscan plug-in option to the existing C5680 Hamamatsu streak camera mainframe. By locking this module to the 81.25 MHz subharmonic of the rf system, the synchronous summing of micropulses could be done with trigger jitter of <1.5 ps (FWHM) for both the UV drive laser component at 263 nm and the e-beam via optical transition radiation (OTR) measurements [2,4]. This jitter is significantly lower than the 10–20 ps trigger jitter found in a fast single-sweep unit which precluded direct summing of the sub-10 ps pulses in the past. The synchronous summing of the low OTR signal from the 15 MeV electron beam micropulses allowed the needed bandpass filters to be utilized to reduce the chromatic temporal dispersion effects inherent to the broadband OTR source and the transmissive optics components. In addition, the C6768 delay module with phase feedback was also implemented, and this unit stabilized the streak camera sweep relative to the master oscillator so that camera phase drift was much reduced to the ps level over 10 s of minutes. This latter feature allowed a series of experiments to be done on the bandwidth effects and transit-time effects in the respective transport lines which require longer term phase stability. After characterizing the UV laser bunch length, a series of e-beam experiments on the A0 beamlines were performed. In the course of our experiments, we did a series of tests on the chromatic temporal dispersion effects for this particular input optics barrel with UV transmitting optics and our optical transport lines. We show our effects were less than that reported at Stanford Synchrotron Radiation Lab with optical synchrotron radiation (OSR) [5], but ours still had to be characterized carefully to allow accurate bunch-length measurements using OTR. We have now installed an all-mirror input optics barrel to mitigate the effects. In addition, we obtained and implemented the slow horizontal sweep plug-in unit that allowed dual-sweep measurements of the micropulse phase and bunch lengths during the beam macropulse. We also describe the use of an ultrafast Ti:Sa

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laser to characterize the streak-tube temporal response, and we report initial steps in synchronizing this laser pulse with the drive laser and electron beam via OTR.

2. Experimental considerations

The tests were performed at the Fermilab A0 photoinjector facility which includes an L-band photocathode (PC) rf gun and a 9-cell SC rf accelerating structure which combine to generate up to 16 MeV electron beams [2]. The drive laser operates at 81.25 MHz although the micropulse structure is usually counted down to 1 MHz. Previous bunch length measurements of the drive laser and e-beam [6,7] were done with the fast single-sweep module of the Hamamatsu C5680 streak camera with an inherent shot-to-shot trigger jitter of 10–20 ps. Such jitter precluded synchronous summing of the short pulses. We have upgraded the camera by acquiring the M5676 synchroscan module tuned to 81.25 MHz with a trigger jitter of less than 1.5 ps (FWHM) and the C6878 phase-locked delay unit which stabilizes the camera phase over 10 s of minutes. Due to the low, electron-beam energies and OTR signals, we typically synchronously summed over 50 micropulses with 1 nC per micropulse. The initial tests were performed in the straight-ahead line where energizing a dipole sends the beam into a final beam dump. The setup includes the upstream corrector magnets, quadrupoles, rf BPM, the YAG:Ce/OTR imaging stations, and the beam dump as schematically shown in Fig. 1. The initial sampling station was chosen at X9, and an optical transport system using flat mirrors and a parabolic mirror brought the light to the streak camera. A short focal length quartz lens was used to focus the beam image more tightly onto the streak camera entrance slit. The quartz-based UV–vis input optics barrel transferred the slit image to the Hamamatsu C5680 streak camera's photocathode. One of the upgrades was to change this optics to all mirror input optics.

Alternatively, the four dipoles and the TM_{110} cavity of the emittance exchange line could be powered and experiments done at an OTR station, X24. After the fourth dipole a second optical transport line brings the OTR to the streak camera. The EEX process in this case exchanges the transverse x and longitudinal phase spaces when the transverse deflecting cavity is powered in the middle of the double dogleg. Our initial transverse emittance is smaller than that of the initial longitudinal emittance, so the EEX normally results in a shorter electron bunch. In the EEX line the bunch compression effects were observed, and the shorter bunches were used to help delineate the chromatic temporal dispersion effects for various band pass (BP), long pass (LP), and short pass (SP) filters. The OTR converter is an Al-coated optics mirror with a 1.5 mm-thick Zerodur substrate or a 0.25 mm-thick Si wafer substrate, and it is mounted with its surface normal at 45° to the beam direction on a stepper assembly. The assembly provides vertical positioning with an option for a YAG:Ce scintillator crystal position. A 2-position actuator and a 4-position translation stage were used in the optical path in front of the camera to select the band pass filters. The OTR streak camera images were recorded with a PCI-based video digitizer for both online and offline image analyses. The charge was monitored by an upstream current monitor. We describe a phased approach over time for our streak camera upgrades and characterizations in the following sections.

2.1. *Resolution and bandwidth effects*

One of the first steps in verifying streak camera operations with OTR is to determine the static spread function contribution to temporal resolution. This is basically the combination of the vertical size of the entrance slit and the focusing of the photoelectrons as mapped through the streak tube when in streak camera "focus" mode. The major contribution to the final vertical spot size is the slit height itself for values larger than 30 μm or so. In our early experiments with 10–50 nC of charge integrated in the micropulse sum, we used a slit height of 80 μm, which resulted in a limiting vertical spot size of 9 pixels. The limiting time resolution is then found by multiplying this by the sweep-speed calibration factor. We did a careful determination of the two fastest ranges, ranges 2 and 1 by using a laser pulse-stacker configuration. By splitting the 263 nm laser beam energy, we could separately delay one pulse relative to the other by a set of movable mirrors. We then tracked the observed pulse separations in the streak camera images. Plots of the observed time separations are shown in Fig. 2 for range 2 (top) and for range 1 (bottom). The reciprocals of the fitted slopes gave us 1.55 ps/pixel and 0.32 ps/pixel, respectively. This means our initial resolution terms were 14.0 ps and 2.9 ps (FWHM), respectively. In the second series of experiments we reduced the slit height to 40 μm with a corresponding vertical spot size of 4.7 pixels (FWHM). This then gives us resolution terms of 7.3 ps and 1.50 ps (FWHM), respectively, for ranges 2 and 1. This was needed for the bunch compression tests particularly.

One of the practical issues we addressed was the chromatic temporal dispersion that occurred for the broadband OTR light as it was transported through the transmissive components of the optical transport line. Since the input optics barrel of the streak camera initially was actually UV transmitting, it consisted of quartz optical components. This material has less variation of index of refraction with wavelength than flint glass or other

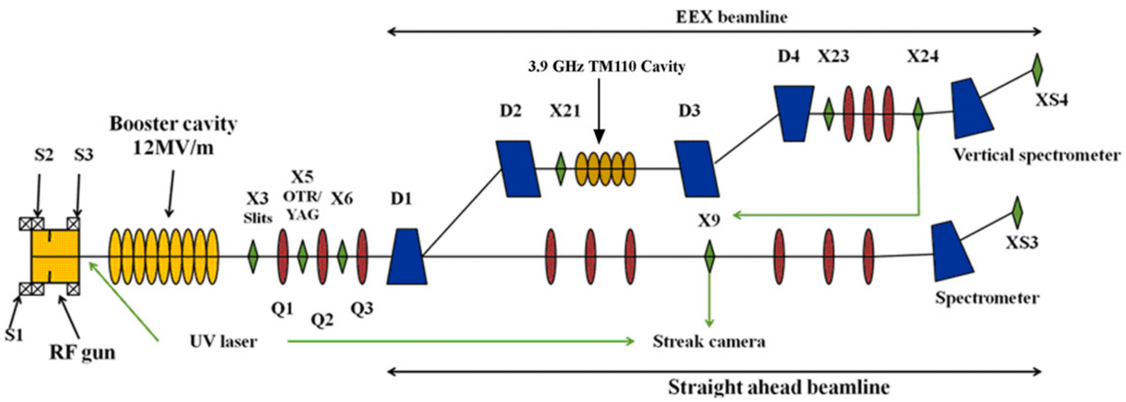

Fig. 1. A schematic of the A0 photoinjector test area showing the PC rf gun, 9-cell Tesla booster cavity, transverse emittance stations, the OTR stations, the streak camera, and the EEX beamline when the two dogleg's dipoles are powered.