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APPLICATIONS OF LASERS TO ACCELERATOR PHYSICS AT SSRL*

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Abstract

Recent advances in accelerator physics and synchrotron radiation research have increased the need to integrate high-power lasers into the technology development program at SSRL. On the injector side, several laser systems have been used to test different photocathode materials and photo-assisted emission from a dispenser cathode RF gun. For the storage ring, both a Ti:Sa laser and a fiber-based laser have been used to measure short-pulse electron bunch lengths in cross-correlation geometry. Both of these lasers have also been used for x-ray pump/probe experiments. In this paper we review laser applications to accelerator physics at SSRL and outlook for the future.

INTRODUCTION

Lasers have been an integral part of accelerator technology for many years. From early on lasers were used for precision alignment of linear accelerators and alignment of magnets and vacuum chambers in storage rings. In terms of laser-electron beam interactions, linac applications range from Compton backscattering to FEL seeding, beam heating, photocathode guns, electro-optic sampling for bunch length and arrival time measurements, fiber-based timing systems, pump/probe experiments and drive beams for laser/plasma accelerators. For storage rings, lasers are used again for Compton back-scattering (both SR applications and diagnostic purposes), femtoslicing, THz and cross-correlation bunch length measurements, timing applications, and more recently short pulse, high-rep rate pump/probe experiments in the x-ray regime.

Some of the principle properties that motivate the application of lasers to accelerator physics are the high degree of transverse photon coherence (low divergence, M~1) and high degree of longitudinal coherence (narrow bandwidth, pondermotive buckets). Of particular importance, the few nJ output of short pulse IR laser oscillators can be amplified via chirp-pulse amplification to 10's of mJ and frequency-multiplied into the visible and UV spectral regions in conjunction with optical parametric amplifiers. Pulse width can vary from ~50-500fs (compressed Ti:Sa and fiber lasers) to 6-10ns (YAG) and pulse repetition rate can vary from 1-100Hz (photocathode guns) to 1-10kHz (femtoslicing) to 5MHz (pump/probe experiments) to CW. Synchrotron radiation by contrast has some 'laser-like' properties (partial transverse coherence, possibility to narrowband filter) but is stochastic in nature with coherent emission possible by CSR or FEL action.

In this paper we focus on two different applications of lasers to accelerator physics at SSRL. The first is photocathode gun development for the injector linac and with high quantum efficiency surface coatings. The second application is bunch length measurement via laser/SR cross-correlation. The later program is coupled to short-pulse, high repetition-rate pump/probe experiments.

PHOTOCATHODE GUN DEVELOPMENT

One of the first applications of lasers to accelerators at SSRL was construction and operation of the SLAC Gun Test Facility (GTF) in preparation for LCLS. At first the GTF utilized a laser oscillator stationed at the SPPS with light pulses transported via fiber-optic link. The oscillator pulses were stretched, fed as seed-laser pulse train to a 1.054μm Nd:glass regenerative amplifier and then re-compressed before second- and fourth-harmonic generation to 263nm. The multi-pass regen amplifier contained two flash lamp heads and operated at 2.5Hz, synchronous with the 2856MHz frequency of the RF gun. A separate single- or double pass amplifier head external to the regen could increase the IR beam energy 15mJ/pulse. The SPPS seed beam was then replaced with a 119MHz, 115mW passively mode-locked IR oscillator using newly-emerged SESAM technology. A co-linear HeNe laser beam simplified alignment by the allowing possibility to work in a visible Class I mode. Over time the SLAC GTF yielded sufficient photocathode performance data and experience to proceed with the more advanced dual-feed LCLS gun. A summary of results from the GTF laboratory can be found in [1].

Similar to tests carried out at MaxLab [2], the next project aimed to operate the thermionic dispenser cathode RF gun in cold-cathode photo-emission mode. The RF gun nominally produces a 2μs s-band bunch train with a strip-line chopper sweeping the beam across discriminating slits to select 3-5 bunches for acceleration in a 120MeV linac and subsequent capture in a single 358MHz booster bucket. By operating in photo-emission mode, the gun can in principle produce single s-band buckets or short 'bursts' of s-band buckets with the potential to fill one or more booster buckets in a single injection cycle. The goal is to minimize the number of injection kicker pulses in SPEAR3 during top-up and optimize injection efficiency.

First tests of cold-cathode operation in photo-emission mode utilized the GTF oscillator/regen system described

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above. With the pulse length compressed to <2ps and UV pulse energies of up to 100uJ at the GTF gun cathode it was possible to measure both electron emission as a function of gun RF phase, and charge and emittance as a function of laser pulse energy [3]. Of particular interest, space charge effects limited an otherwise linear response to laser pulse energy at ~8μJ with a quantum efficiency of QE~$4.5x10^{-4}$ [3].

The next set of tests used a Thales JEDI laser on loan from the LCLS. This photodiode-pumped frequency-doubled YAG laser can deliver up to 100mJ/pulse at 120Hz with 532nm output wavelength. The 120Hz YAG pump was synchronized to the 10Hz electron gun using a burst generator to output 12 pump triggers at every 10Hz clock pulse. A 10Hz Pockels cell trigger produced somewhat lower output pulse energy but up to 350μJ/pulse could be generated in the UV using a thin BBO crystal to frequency-double the output. Dichroic mirrors were used to reject the 532nm component. With careful tuning and alignment up to 100μJ was available at the vacuum input window leading to the SSRL injector cathode.

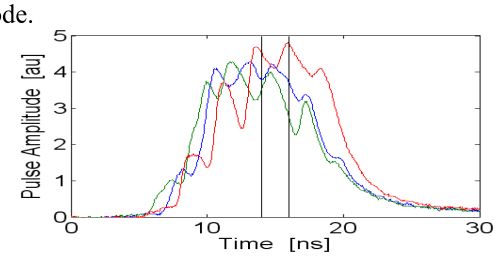

Figure 1: Pulse-to-pulse jitter mode from YaG laser. Black bars indicate chopper. Courtesy S. Gierman.

Several differences were noted between the 2ps short-pulse Nd:glass and the 7ns YAG laser tests. For the 2ps Nd:glass laser the light pulse must arrive at the correct RF phase. With the 7ns YAG laser each UV pulse spans approximately twenty 350ps s-band buckets. Electron emission occurs whenever the RF field has favorable magnitude and phase during the laser pulse duration. As indicated in Fig. 1, the YAG laser output exhibits random longitudinal mode-phasing causing shot-to-shot fluctuations in the temporal profile. Since the chopper selects only 3-5 s-band bunches (1-1.7ns) the resulting charge and electron beam energy fluctuations can be significant. Despite these effects, the injection rates into SPEAR3 were observed to be as much as or exceed rates in the thermionic mode. More recently the JEDI has been returned to the LCLS as a back-up pump laser and a similar YAG laser, quadrupled to 266nm, installed to continue the cold-cathode tests.

In a parallel cathode development program, a copper surface coated with 18nm CsBr is being tested for QE enhancement. First tests were carried out with a 2W continuous-wave visible ion laser doubled to produce up to 100mW of 257nm CW in the UV. Next, after surface activation of the CsBr with the doubled ion laser, the photocathode chamber was transferred to the GTF laboratory for testing with the 7ns YAG laser. Preliminary results indicate a QE enhancement by as much as a factor of 15-20 with only 1-5μJ/UV pulse incident on the cathode [4]. Further testing will be carried out with either the 2ps oscillator/regen system at the GTF or at another laboratory within SLAC to study the short pulse, high peak power QE and surface longevity of the CsBr cathode before installation in an active RF gun.

SHORT PULSE MEASUREMENTS AND PUMP/PROBE EXPERIMENTS

When SPEAR3 operates in the low-momentum compaction mode, the electron beam bunch length can be reduced from 20ps rms to ~1ps rms with approximately 10μA single-bunch current [5]. Although the SR flux is relatively low, short-pulse, high repetition-rate x-ray pump/probe experiments can be carried out in conjunction with high-power femtosecond laser sources. This work is particularly important for time-resolved chemistry and materials science research and can be used as a staging ground for very short pulse x-ray pump/probe experiments with GW beams at the LCLS [6].

For many applications it is important to know not only the laser pulse arrival time relative to the x-ray probe beam but also the precise SR pulse length. Streak cameras operating in synchroscan mode can resolve timescales down to a few ps but no less. At shorter bunch lengths, as demonstrated by Zolotorev [7], the relatively weak SR pulse can be cross-correlated with a short, high power laser pulse in a non-linear optic to generate an output signal proportional to the number of photons in a narrow slice of the SR pulse. By scanning the arrival time of the laser pulse across the longer SR pulse the longitudinal bunch profile can be reconstructed.

The first set of cross-correlation measurements utilized an 800nm mode-locked Ti:Sa long-cavity oscillator synchronized to the storage ring clock [8]. The Ti:Sa oscillator/amplifier system produced a train of 500nJ, 60-fs pulses at 5.1MHz (four times the SPEAR3 ring frequency). For this application, the 93^{rd} harmonic of the laser signal was mixed with the 476.31MHz storage ring RF, and a piezoelectric-actuated mirror maintained the oscillator cavity length to minimize the feedback error signal. The overall system jitter was estimated to be <1ps.

The 800nm Ti:Sa beam was then passed through a retro-reflective delay stage to control arrival time relative the 800nm SR beam. As shown schematically in Fig. 2, the cross correlation signal was generated by mixing the two beams in a non-centrosymmetric BBO crystal exhibiting $\chi^{(2)}$ nonlinearity. The non-collinear geometry of the two 800nm input beams allowed the 400nm product beam to be spatially separated by means of an iris.

After further spectral filtering to isolate the 400nm photons, an avalanche photodiode (APD) detected the weak mixing signal. A high-frequency lock-in amplifier clocked at the 1.28MHz ring frequency was used to isolate the cross-correlation photons. With this system it was possible to resolve pulse lengths down to σ=5.94 ps rms at 86uA in a single bunch.

The cross-correlation photon flux can be estimated as follows. Each Ti:Sa beam contains ~10^{12} photons/pulse. Based on the measured SR power, the diagnostic beam line collects ~10^{7} SR photon/pulse/mA. Of these, only about ~10^{6} photons pass through the 800nm bandpass filter. Assuming the low-power BBO conversion efficiency is linear with pump intensity, typical efficiencies for SHG production lead to about 10^{-3} 400nm photons/pulse at low electron bunch currents.

A subsequent revision of the cross-correlation measurement featured a 1030nm, 500fs fiber laser producing 2μJ/pulse at 1.28MHz [9]. The fiber laser was again locked to the 476MHz master oscillator, this time limiting jitter to a few hundred fs. A Type-II BBO crystal designed for sum-frequency generation was installed to reduce background effects from SHG of the laser light as it passed through the BBO. The input wavelengths to the crystal were 1030nm (IR laser) and 515nm (visible SR) which combined to generate 343nm cross-correlation photons, again at the rate of ~10^{-3} per event.

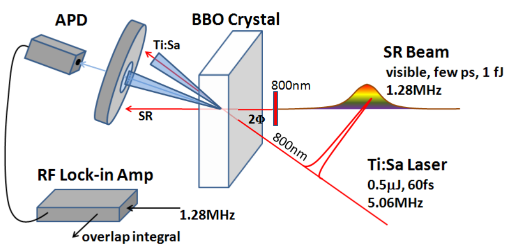

Figure 2: Mixing with am 800nm Ta:Sa laser.

Several other features of the fiber laser system lead to improved measurement resolution. These included replacement of the problematic retro-mirror delay line with a programmable RF delay unit giving 250fs resolution, and installation of a 25μm diameter pinhole to provide a more consistent beam overlap. A Hamamtsu SPCM single-photon counter coupled to a fast time digitizer recorded the TTL output pulses from each cross-correlation event. The need for lock-in amplification of the 343nm product signal was eliminated by taking advantage of the wavelength separation inherent in the sum-frequency configuration. In the best case it was possible to resolve a ~1.2ps rms rising edge on the SR pulse [9]. The overall width or 'flat top' of the measurement was dominated by synchrotron oscillations.

With short pulse, high-repetition rate x-rays now available at SPEAR3, pump/probe chemistry and materials science programs are underway. Both the Ti:Sa and fiber lasers mentioned above have been moved to different SR beam lines to optically 'pump' material samples (Figure 3). The short pulse x-rays then 'probe' the sample to determine time resolved response. For fast imaging with a gated Pilatus area detector, the 5.1MHz Ti:Sa laser operates at the upper rate limit of the detector. With the 1.28MHz fiber laser, pump/probe measurements have been made with either a single high-current bunch isolated from the main bunch train or a single isolated low-current bunch in short pulse mode.

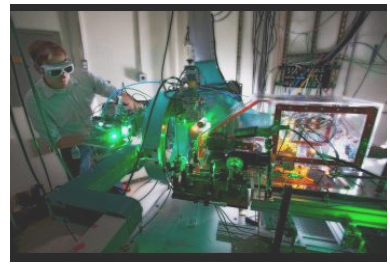

Figure 3: Pump/probe experiments at SPEAR3.

SUMARY AND FUTURE PLANS

Short-pulse, high power lasers are becoming an increasingly common part of both linear and circular accelerator systems. Applications include charged particle beam manipulation, control of photon emission processes and diagnostics. At SPEAR3 both photocathode gun research (including cold-cathode and CsBr deposition tests) and pulse length diagnostics via laser/SR cross-correlation measurements are underway. To assist the pump/probe materials science and chemistry programs, laser-based tests will be made to detect and transmit bunch arrival time to pump lasers deployed on x-ray beam lines around SPEAR3.

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