LASER SYSTEMS AND ACCELERATORS

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Abstract

Laser systems play a key role in the operation and the design of present-day single-pass Free Electron Lasers (FELs). The application of lasers includes the generation of electron bunches, the direct manipulation of electron bunch properties, the implementation of laser based measurement tools, and the synchronization of machine systems on the femtosecond level. In this paper, an overview of laser systems and their applications in FELs is presented.

INTRODUCTION

In recent years, tremendous effort has been taken to develop the applications of laser systems for single-pass FELs in order to expand their operation range, to increase the FEL photon quality, or to decrease the overall costs of the facility. With the use of RF photo-injectors for the production of high-brightness electron bunches, lasers have become an integral part of FELs. Consequently, the laser system stability has become a central criteria for the choice and the layout of the laser system.

The application of lasers in FELs can be categorized in five different groups:

1) Photoinjector lasers: Electron beams are produced by impinging short-pulse lasers onto photocathodes in RF guns. The requirements of low thermal emittance but large bunch charge demands laser pulses with wavelengths in the ultra-violate range. Space-charge induced emittance growth in RF guns is greatly reduced through longitudinal and transverse pulse shaping.

2) Lasers for beam manipulation: The targeted conditioning of electron beam properties usually relies on the inverse FEL process. An external laser beam passes collinearly with an electron bunch through an undulator or a wiggler whose resonance is tuned to the laser wavelength. The laser impresses an energy modulation onto the electron bunch. The energy modulation is used to artifically increase the longitudinal phase space (laser heater), to locally enhance the bunch current (E-SASE) [1], to provide fully longitudinally coherent FEL radiation (Seeding) [2], or to produce FEL pulses with attosecond duration [3].

3) Beam diagnostics: The ultra-short duration of electron bunches that drive FELs puts new demands on the beam instrumentation. The frequency bandwidth required to diagnose the longitudinal electron bunch profile exceeds several terahertz. Using an optical carrier frequency (100-200 THz) and novel laser diagnostic techniques allows for precise parasitic measurements of electron bunch length.

4) Lasers for two-color experiments: For many applications in atomic, molecular, and solid-state physics, the XUV and X-ray FEL radiation is used to probe the state of physical samples that have been excited by optical lasers in a pump-probe configuration. The parameters of the lasers differ significantly depending on the application. Studies of ultra-fast electronic process require pulse duration of few tens of femtosecond but moderate power levels (0.1-1.0 mJ) while lasers for plasma physics investigation operate with pulse energy of tens of Joules.
To study fast evolutionary processes the delay between optical and FEL pulses is varied. The precision of the measurement depends critically on the synchronization between both sources.

5) Synchronization: The high carrier-frequency of optical radiation, the low-loss broadband signal travels in fibers, and the availability of high-precision phase detectors makes lasers ideally suited for the synchronization of the various subsystems in the accelerator. They open the pathway to femtosecond synchronization within facilities of several hundred meters length.

The many possible laser applications at FELs, the diversity of the laser systems, the complexity and stringent demands on stability has caused accelerator laboratories to form close collaboration with laser institutes and to setup small laser groups for maintenance and in house R&D.

PHOTO-INJECTOR LASERS

The photo-injector laser requirements depend on the envisioned operation mode - low or high repetition rate - and the type of photocathode. Copper cathodes are often used in S-band guns, which are operated at field gradients up to 120 MV/m. The quantum efficiency,the electron emission probability per incident photon, at 260 nm for copper cathodes is relatively low, between 10^{-4}-10^{-5}. A UV laser pulse energy of about 0.2 mJ is required to produce a 1 nC electron bunch. For high repetition-rate FELs, semiconductor photocathodes, cesium tellurid (Cs_2Te) are used in an L-band gun with a lower field gradient (40-60 MV/m). The quantum efficiency of Cs_2Te is about a percent [4] and laser pulse energies below 1 μJ are sufficient for a 1 nC bunch charge.

Low repetition rate high power laser systems

Short pulse durations of 10 ps (FWHM), and fast rise-times of 1 ps or less require a gain medium with bandwidth of several THz, as in titanium-doped sapphire (Ti:Sa). A laser system scheme for low repetition-rate (1-100 Hz) but large pulse energies (E_{IR}=20-50 mJ) is shown in Fig. 1 [5].

A continuous stream of short laser pulses with a central frequency of 800 nm (tunable) is generated in a passive

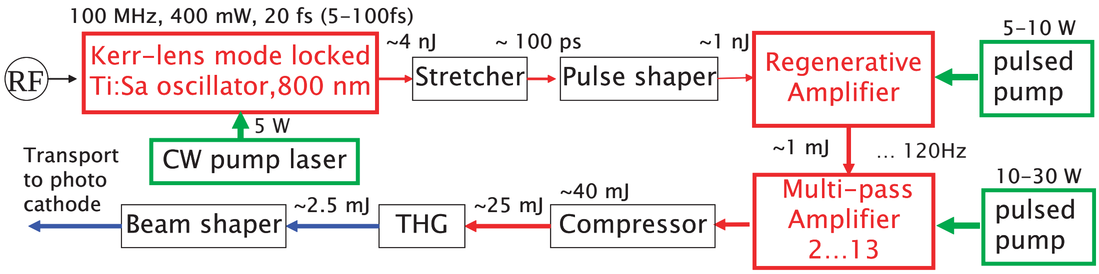

Figure 1: Typical layout of photocathode laser system for Cu-cathodes.

mode-locked Ti:Sa oscillator. Passive or self-mode locking - the phase-coherent locking of the resonator modes - is usually established by an intra-cavity aperture that causes self-amplitude-modulation of the laser beam due to the optical Kerr-lens effect in the Ti:Sa crystal. The simultaneous oscillation of a large number of phase-locked longitudinal modes in a laser yields a field equal to zero most of the time except for very short periods that contain the entire energy of the radiation field in the oscillator. The frequency spacing between the modes is equal $1/T_r$, where T_r is the resonator round-trip time. The laser pulses exit the oscillator through a partially reflecting mirror.

To synchronize the laser to the accelerator RF, a small fraction of the laser pulse-stream is focused onto a fast photodiode. The current pulses from the photodiode are band-pass filtered, amplified and mixed with the RF oscillator signal. The resultant error signal is used to control the laser resonator length via a piezo-electric crystal that moves one of the cavity mirrors.

To avoid damage of the gain medium through non-linear processes, the laser pulses are first stretched to ≈100 ps by a grating or prism arrangement and longitudinally shaped in a pulse shaper before launching into the amplifier system. A regenerative amplifier - the initial pulse is injected with a Pockel cell into a cavity and ejected after tens to hundreds of round-trips, each passing the Ti:Sa crystal for amplification - providing a gain factor of about one million to 1 mJ pulse energy. The energy is then boosted to several tens of Joules in a multi-pass amplifier.

After amplification, the pulse is compressed in a pair of gratings before passing the frequency tripling crystals that convert the IR (800 nm) to UV (266 nm). A transverse flat-top pulse shape of the beam is accomplished by aspheric lenses and a pulse shaping aperture before the transport of the laser beam into the accelerator tunnel [6]. A mirror mounted at the RF gun exit is used to launch the laser onto the cathode. The transport system images the pulse shaping aperture onto the cathode. A fraction of the laser beam is tapped onto a screen that is imaged by ccd to control the transverse shape of the laser pulse (virtual cathode).

High repetition rate burst-pulse mode lasers

The laser system at FLASH generates a stream of laser pulses with spacing of 0.3-1 μs in an 800 μs long burst with a repetition rate of 10 Hz (Fig. 2). The custom - made laser system was developed by the Max-Born Institute in Berlin. The building blocks of the laser systems are: a diode-pumped, active mode-locked pulse-train oscillator, a two-stage diode-pumped amplifier chain followed by two flashlamp-pumped booster amplifier, and a wavelength quadrupling stage to convert the IF (1047 nm) into UV radiation [7].

The laser material used in the system is neodymium-doped yttrium fluoride (Nd:YLF). The material can be efficiently pumped by both flashlamp and semiconductor diodes (805 nm). The large emission cross-section permits single-pass amplification in a Nd:YLF-rod that exceeds a factor of 10. The small duty cycle of 1% of the burst pulse mode operation reduces significant the average thermal heat load generated in the laser crystals and the amplifier chain permits delivery of up to 300 W laser power.

The oscillator repetition rate is 27 MHz in a 4-times folded geometry, passively length stabilized with quartz rods and actively stabilized by a slow piezo actuator compensating for residual drifts. Active mode-locking is performed with slow acousto-opic mode-lockers AOM1 and AOM2 at 13.5 MHz and 108 MHz. A fast electro-optic phase modulator at 1.3 GHz shortens the laser pulses and provide the synchronization to the acceleration RF ($<$ 200 fs rms [13]).

To generate a stable, long pulse-train, the oscillator is pumped 2 ms before the first laser pulse is launched to the RF gun. The train starts with a relaxation oscillation that settles after about 500 μsec. The stable train with 0.28 μJ pulse energy exiting the oscillator is picked with a repetition rate of 1-3 MHz using fast Pockels cells and sent to the amplifier system. Two diode end-pumped amplifiers increase the energy to 6 μJ, which is then boosted to 300 μJ by two flashlamp pumped Nd:YLF rods. Stable laser pulse energy across the pulse train is adjusted by careful selection of the pre-trigger activating the precisely controlled flashlamp current power supplies.

Refractive effects due to variation of temperature distribution during the pump process (thermal lensing) are minimized by a telescope that successively images the beam from one amplifier to the next and finally into the frequency conversion crystal. To minimize pulsation of the beam profile, a beam shaping aperture that selects the central part of the beam is mounted directly at the entrance window of the

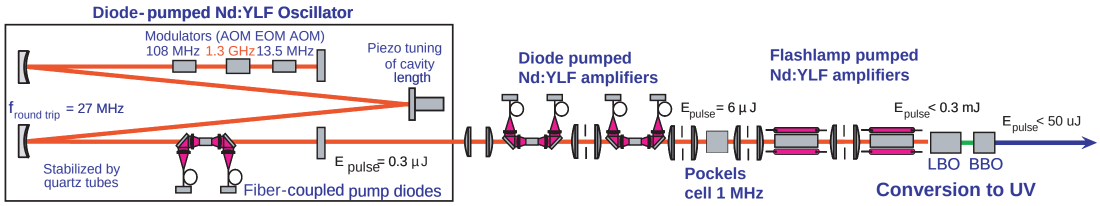

Figure 2: Photocathode laser system of FLASH.

photo-injector.

The fourth harmonic of the fundamental wavelength radiation is generated using a 10 mm lithium triborate crystal (LBO) to convert the IR to green and then a 6 mm BBO-crystal to yield the UV light. The angular acceptance angle of the BBO is 0.27 mrad only and requires careful alignment and occasional readjustment. Demagnifying the laser beam diameter out of the amplifier chain by a factor of 2.5 to 2 mm at the LBO crystal a conversion efficiency of 16-18% is achieved. The pulse duration is 10.5 ps (FWHM) as measured with a streak camera.

Longitudinal pulse shaping

Numerical simulations of RF guns show that space-charge induced emittance growth can be reduced by laser pulse shapes with a long flat top region (10-20 ps) and short rise and fall times (0.5-2 ps). Laser pulses exiting an oscillator usually have gaussian or secant shapes. Powerful tools to shape the laser pulses based on Fourier optics have been developed over the past years [8, 9]. Pulse shaping is based on the amplitude and phase modulation of the input pulse spectral components. Let $E_{in}(t)$ denote the electric field of the laser pulse with central frequency ω_0, an intensity distribution $I(t)$ and a time dependent phase shift $\phi(t)$ (e.g. for chirped lasers pulses $\propto t^2$)

$$E_{in}(t) = \sqrt{I(t)}e^{i(\omega_0 t+\phi(t))} . \qquad (1)$$

Linear pulse shaping is expressed by $H(t)$ the impulse response function of the shaper. The output laser pulse is obtained by convolving E_{in} with $H(t)$ yielding a multiplication in frequency domain:

$$E_{out}(\omega) = \sqrt{I(\omega)h(\omega)}e^{-i(\psi(\omega)+\phi(\omega))} . \qquad (2)$$

For example, a rectangular pulse response of the filter with duration T_0 in time domain yields a sinc function in frequency domain

$$H(\omega) = \frac{\sin(\omega T_0/2)}{\omega/2} \qquad (3)$$

with alternating sign (phases shift of π). Thus, amplitude modulation alone is insufficient to create a flat head pulse shape. Similar arguments hold for shaping using primarily phase modulation.

For limited input bandwidth of the laser pulse, the output of a shaper represented by sinc filter will have smooth rising and fall times. If the filter function is truncated, e.g. because the dynamic range of the filter is insufficient to cover the complete bandwidth of the laser pulse, then undesirable oscillations are added to the flat-top [11]. The large bandwidth of the laser pulse can also lead to distortions in the frequency tripler or quadrupler due to phase matching and group delay limitations in the non-linear crystals [12].

Figure 3 shows three different types of pulse shapers: (a) A zero-dispersion apparatus in 4f configuration. The incident laser pulse is spatially dispersed by the first grating and lens. Spatially patterned amplitude and phase masks are placed midway between the two lenses at the point where the optical spectral components have the maximal spatial separation. After the second lens and grating, all frequencies are recombined. Programmable liquid crystal spatial light modulator (PLC-SLM) are used to provide optimized mask function. (b) shows an acousto-optic programmable dispersive filter (AOPDF) [10]. The laser pulse is polarized along the fast axis of a birefringent crystal. A time varying acoustic wave is launched with a transducer, collinearly to the propagation of light. The second mode along the slow axis can couple by acousto-optic interaction only in the case of phase matching. The difference of the refractive indices provides the time delay between the frequency components. The coupling strength depends upon the amplitude of the acoustic wave. An AOPDF, therefore, allows for simultaneous control of amplitude and phase. (c) shows a schematic representation of the direct space-to-time shaper (DST) [8]. The field of the input pulse passes a spatial pattern mask before being dispersed by the diffraction grating. The lens performs a spatial Fourier transform on the dispersed frequency components. At the Fourier plane of the lens, the spatial profile of any frequency component is the Fourier transform of the input spatial profile. The thin slit gives a spatially uniform output spectrum that is the Fourier transform of the input spatial profile.

AOPDF and DST are presently considered for pulse shaping in the IR. Both have been successfully used, even though the stability of the method for routine operation is still a critical issue. Feedback systems to control the parameters of the shape by measuring the output pulse shape are, therefore, considered.

LASER HEATER

The residual energy spread of an electron bunch exiting an RF-photoinjector is on the order of a few keV [14]. With an increased energy spread, Landau damping can overcome potential micro-bunch instabilities driven by space charge

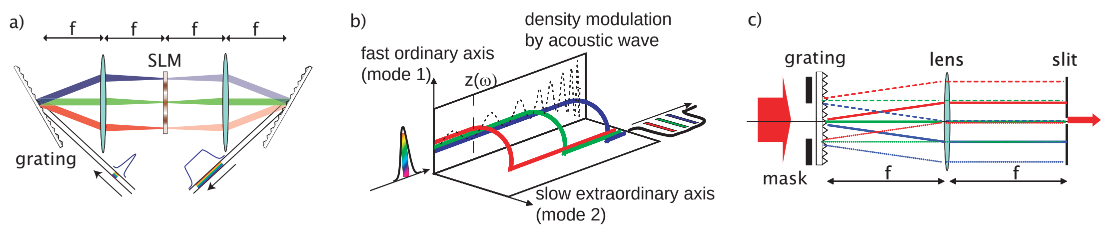

Figure 3: Scheme of different techniques for longitudinal pulse shaping of laser pulses: a) dispersion free pulse-shaper using a spatial light modulator, b) acousto-optic programmable dispersive filter and c) direct space-to-time pulse-shaper.

accumulated along the linac and coherent synchrotron radiation in the bunch compressors. A laser heater, sketched in Fig. 4, works like an inverse free electron laser [15, 16]. A sufficiently strong laser pulse passes collinearly to the electron bunch through an energy-modulating undulator. The energy modulation impressed into the electron beam is smeared by the transverse field strength dependence of the laser pulse. This is most efficient when the laser waist approximately matches that of electron bunch.

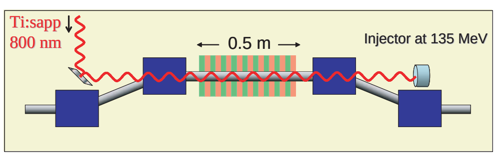

Figure 4: Scheme of laser heater (LCLS)[16]

Installation of the undulator in a chicane has two advantages: first, it provides an easy way to couple the laser beam into the vacuum chamber, and second, the dependence of the path length on the electron angle (matrix element R_{52}) through the last two dipoles of the chicane erases all remaining time-energy correlation in the bunch and produces an effective 'thermal' residual energy spread [17].

The resonance of the undulator is tuned to the laser wavelength. The amplitude the laser induced energy modulation is [16]

$$\triangle\gamma(r) = \sqrt{\frac{P_L}{P_0}} \frac{KL_u}{\gamma_0\sigma_r} \left[J_0\left(x\right) - J_1\left(x\right)\right] e^{-\frac{r^2}{4\sigma_r^2}} \qquad (4)$$

with $x = K^2/(4+2K^2)$, where $P_0 = I_A mc^2/e \approx 8.7\,\mathrm{GW}$, $J_{0,1}$ are the Bessel function, and r the radial position of the electron.

The laser power needed to increase the residual energy spread to few tens keV is moderate (0.5-1.5 MW). With a laser pulse duration of 20-30 ps FWHM to cover the entire electron bunch the required pulse energy is less than 50 μJ.

The residual energy spread increases by a factor $C \approx 30 - 100$ through the longitudinal compression in downstream magnetic chicanes. The FEL process is not compromised when the relative residual energy spread is much smaller than the free-electron laser parameter $\rho \approx 5 \cdot 10^{-4}$. This sets an upper limit, between 10 keV and 50 keV, on the allowable increase of the energy spread by a laser heater.

LASER FOR BEAM DIAGNOSTICS

Lasers have been used to measure the longitudinal and the transverse beam profile. In this paper, only longitudinal measurements will be described since transverse (laser-wire) measurements have not been implemented in FELs.

For high beam energies, the co-propagating electromagnetic fields of the electron bunch are proportional to their longitudinal charge density. By encoding the field amplitude into the laser pulse, the charge profile is obtained optically. In an electro-optic technique, the radial electric field of the electron bunch changes the birefringence of a crystal through which a laser propagates. The polarization of the laser pulse is converted to an amplitude modulation after passing a polarizer. The amplitude modulation is then detected by a photodiode or a camera. Electro-optic techniques allow for single shot measurements by encoding and decoding the time-dependent electric field in a single laser pulse. Electro-optic measurements are non-disruptive and well suited to determine the arrival-time of the electron bunch. The temporal resolution is currently limited to 120 fs FWHM due to phonon resonances in the crystals.

Another technique creates an optical replica of the electron bunch [18]. First, the electron beam energy is modulated by an intense laser beam in a short modulator undulator. The energy modulation of the electron beam creates a density modulation in a downstream magnetic chicane. In a second undulator, the density modulated electron beam radiates at the wavelength (or a harmonic) of the laser beam. The laser pulse created in the second undulator is Fourier-limited and has the longitudinal density profile of the electron bunch. It is detected by single-shot optical cross-correlation or frequency resolved optical gating (FROG) [19]. The resolution of this method is limited to 5-15 fs FWHM by the slippage of the electron bunch in the radiator undulator. An optical replica experiement is planned at FLASH in 2007 [20].

SYNCHRONIZATION SYSTEM

If the accelerator facility exceeds several hundred meters, but the synchronization requirement is well below 100 fs, RF based scheme are insufficient to stabilize the various sub-systems in the accelerator with respect to one another. Optical clock distribution systems can synchronize devices with femtosecond precision [21].

The synchronization signal is encoded either by amplitude modulation of a CW laser beam with an electro-optical modulator or it is contained in the precise repetition of short laser pulses. Only the latter is treated here, for further details on the frequency-domain approach see [22].

The laser pulse-stream is generated in a passive mode-locked dispersion managed Erbium-doped fiber laser [23]. Passive mode-locking is established by self-phase modulation of the laser pulse travelling in the fiber ring oscillator where a polarizer cube in a free space section acts as an artificial saturable absorber. Self-phase modulation is proportional to the peak laser intensity, the laser core can pass the polarizer cube while the tails of laser pulses are rejected. In this way, pulse durations below 100 fs FWHM are generated at a central wavelength of 1550 nm where devices from the telecommunication industry are readily available. The repetition rate of the laser is typically 40-100 MHz. The output power amounts to about 40 mW.

Variations of the repetition rate of the pulse stream are determined by measuring the phase noise characteristics of a bandpass filtered and amplified photodiode signal. The timing jitter integrated from 1 kHz to the Nyquist frequency (half the repetition rate) is below 10 fs, limited by the measurement setup (theoretically $<$1 fs)[23]. At frequencies smaller than 1 kHz, ambient noise and thermal drifts cause disturbances which requires one to lock the laser to a low phase-noise RF oscillator.

The laser pulse-stream is distributed in path-length stabilized fibers. To stabilize the fiber length, a small fraction of the laser pulse is reflected at the fiber end and its arrival-time is compared to the preceding laser pulses generated from the oscillator. This method utilizes RF and balanced optical cross-correlation techniques to generate the error signal that drives a piezo based fiber stretcher.

Photodetectors and bandpass filters or optical-to-RF mixers [24] can be used to convert the laser pulse stream to an RF signals where any frequencies $f = N/M f_r$, N and M being integers, can be created. The laser pulse stream can be used to seed other lasers. It is ideally suited to synchronize lasers that can not be seeded by optical-cross correlation [25]. Finally, electro-optical modulators open the path to directly measure the bunch arrival time [26], to determine the beam position in chicanes [27] or to optically sample with high precision the phase of RF cavities.

SUMMARY

In this paper, the different laser application in FELs for generation of the electron beam, dedicated manipulation of energy spread by a laser heater, to diagnose the longitudinal beam properties and for synchronization are described.

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