GUN LASER SYSTEMS FOR THE SWISSFEL PROJECT

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Abstract

The design of the SwissFEL [1] is based on a laser-driven photocathode electron source providing a slice emittance of <0.4 mm.mrad with 200 pC charge. To achieve this ambitious goal two different gun lasers are considered. The first laser is based on a broadband Ti:sapphire amplifier designed to provide unique features such as wavelength-tunability and arbitrary temporal pulse forming in the UV together with a high pulse-to-pulse energy stability. The second system is based on a compact Nd:YLF amplifier offering excellent stability and reliability. Both systems are presently being under evaluation at PSI. Here we present layouts and first experimental results.

INTRODUCTION

The Paul Scherrer Institute (PSI) is considering the construction of a compact and cost-effective X-ray FEL facility, the SwissFEL [2]. As electron gun a copper photocathode will be used illuminated by a powerful ps UV laser. Electron guns based on photoemission have the intrinsic advantage that electron bunch properties, such as transverse/longitudinal shape, charge, nonlinear space charge forces and ultimately the electron beam emittance can be controlled by the laser pulse. In particular, by tuning the wavelength one can vary the emitted photoelectrons momentum distribution with corresponding change in the intrinsic emittance of the gun (K. L. Jensen *et al.*, Appl. Phys. Letters **89,** 224103 (2006)) . The required laser characteristics for the SwissFEL gun are listed in Table 1.

Table 1: Gun laser characteristics for SwissFEL

pulse energy	200 uJ
central wavelength λ	250-300 nm
bandwidth Δλ	2-3 nm
pulse repetition rate	100 Hz
double pulse operation	yes
delay between double pulses	50 ns
laser spot size on cathode (s)	0.1-0.27 mm
pulse rise time	<0.7 ps
pulse duration (FWHM)	3-10 ps
longitudinal pulse form	various
transverse pulse form	uniform
laser to RF phase jitter	<100 fs
UV pulse energy fluctuation	< 0.5% rms
pointing stability on cathode	<1% ptp

Presently, no commercial laser system can provide all requirements listed above. This was the start of the R&D activities presented here. In the first part of this paper we discuss design and preliminary measurements on a prototype Ti:sapphire amplifier which has been built by Amplitude Technologies [3]. The system employs adaptive spectral filtering to reduce gain-bandwidth induced spectral narrowing and offers currently a wavelength tuning range of 760-840 nm. Efforts have been undertaken to improve the overall stability and beam quality of the gun laser. First experimental verifications are foreseen to be performed at the 250 MeV injector facility currently under construction at PSI [4]. The second part presents a compact Nd:YLF amplifier system currently used to drive the SwissFEL 4 MeV diode / RF photogun combination [5].

TI:SAPPHIRE LASER SYSTEM

A Ti:sapphire based amplifier system with subsequent frequency conversion stages is used to reach the required gun laser parameters (Table 1). Ti:sapphire systems are commercially available and have reached a high technological maturity due to their widespread use in research laboratories throughout the world. In addition, many diagnostic tools and pulse shaping techniques are available for the near-IR/visible spectral region and frequency-tripling of the fundamental laser wavelength allows easy access to the UV.

Conventional Ti:sapphire amplifiers, however, suffer from spectral narrowing due to the limited gain bandwidth yielding to spectral width of 30-40 nm (FWHM) at the mJ level. This makes wavelength tuning over the required range impossible. The scheme presented here has the potential to overcome this limitation and offers furthermore enhanced pulse energy stability 1) and direct UV pulse shaping 2). This should help to produce electron bunches with lower emittance at the gun.

General Layout

The laser system (Fig. 1) consists of 4 subsequent amplifier stages. As seed laser, a Rainbow oscillator (Femtolaser, Inc.) delivering 380 mW is used pumped by a 5W Verdi (Coherent, Inc.). To improve the long-term performance of the oscillator a beam pointing stabilizer has been installed on the pump beam consisting of a 4-quadrant photodiode and a piezo-driven mirror mount.

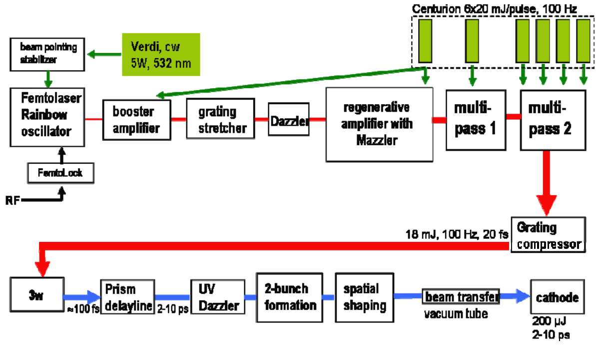

Figure 1: Schematic drawing of Ti:sapphire gun laser system

The pre-amplified (10µJ) and temporally stretched (≈200 ps) pulse seeds the regenerative amplifier. An acousto-optic programmable gain control filter (Mazzler, Fastlite Inc. [6]) is situated in the regenerative cavity and used as an adaptive spectral filter to compensate for spectral narrowing during amplification. The pulses are subsequently amplified in two sequential multi-pass amplifiers and compressed to 20 fs, 18 mJ. Six identical Q-switched, frequency-doubled Nd:YAG pump lasers (Centurion, Quantel, Inc.) are puming the various amplifier stages with a total pump power of 120 mJ.

The compressed pulses wavelength is converted from the near-IR to the UV by second harmonic generation (SHG) in a β-barium borate (BBO) crystal (type I, 0.5 mm, φ=29.2°, ϕ=90°) and subsequent sum-frequency generation (SFG) in a second BBO crystal (type I, 0.5 mm, φ=42°, ϕ=90°). The temporal pulse shape of the fundamental is optimized, for high UV conversion efficiency. This is achieved with the grating based compressor and a Dazzler located after the pre-amplifier. The Dazzler is used to compensate for third-order dispersion avoiding detrimental satellite pulses [4].

Temporal pulse forming in the UV will be done by a low-loss prism-based pulse strecher followed by an acousto-optical programmable dispersive filter (UV-Dazzler, Fastlite Inc.) while transverse homogenisation will be realized by selecting the core part of the intensity profile by a spatial mask [7] which is relay-imaged onto the cathode surface.

Pump Laser Cluster

Each of the Centurion pump lasers provides 20 mJ at 532 nm and 100 Hz. The large number of six identical pump lasers is uncommon for the performance of the presented amplifier system. In principle one single powerful pump laser could provide the required pump energy. However to fulfill the stringent stability requirements of the gun laser we have chosen the following approach: First, compact diode-pumped Q-switched lasers (Centurion) from Quantel [8] have been chosen since they provide lowest rms energy fluctuations (<0.4 % rms) at 532 nm (Fig. 2).

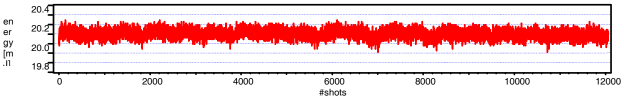

Figure 2: Pulse energy fluctuation of an individual Centurion pump laser over 120 sec (rms ≈0.4%).

Secondly, a total number of six pump-laser increases the stability even further since the net pump energy noise of N pump lasers will be decreased by a factor of $\sqrt{N}$ compared to a single pump laser. (that is to say six pump lasers reduces the noise floor by a factor of ≈2.5). Preliminary measurements show, that the rms stability of the amplified pulse (0.34% rms) is indeed better than the performance of one individual pump laser (0.4% rms) (Table 2).

Wavelength Selection

A control on the central laser wavelength (i.e. the laser photon energy) could be helpful to reduce the intrinsic (thermal) emittance of the photo-electron beam. Electrons leaving the metal surface by photo-emission have a kinetic energy $E_{kin}=\cong\omega-\phi_{eff}$, and thus a thermal emittance $\varepsilon_{th} \propto E_{kin}^{1/2}$ arising from the mismatch of the photon energy $\cong\omega$ and the cathode work function ϕ_{eff}. The intrinsic emittance may then be reduced by adapting the laser photon energy to the effective work function of the cathode material.

Despite the large gain curve of Ti:sapphire crystals (600-1100nm) conventional amplifier systems provide spectra of only 30-40 nm centred around 800 nm due to gain narrowing effects. In our system an acousto-optical gain shaper (Mazzler) implemented in the regenerative amplifier helps to overcome such bandwidth-limiting effects [9]. The Mazzler introduces a wavelength dependent loss inversely to the Ti:sapphire gain curve in order to achieve a flattening of the net gain over a large spectral range. The resulting flattop-like spectrum reaches typically ≥80 nm bandwidth at FWHM (Fig.3). For pulse shaping purpose, however, spectra of 15-25 nm (FWHM) at the fundamental wavelength are large enough to generate flattop UV pulses with a rise time of <0.5 ps.

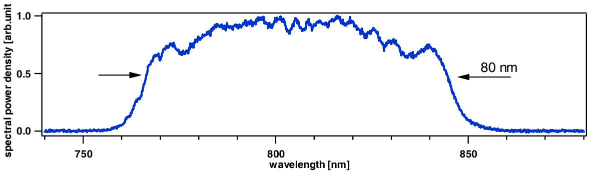

Figure 3: Broadband amplification in Ti:sapphire thanks to acousto-optical gain control

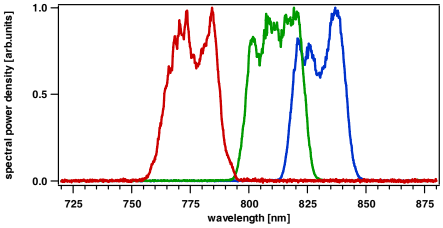

Figure 4: Wavelength-selected narrow-band amplification.

Wavelength selection is performed before the regenerative amplifier by the Dazzler. The current amplifier scheme allows continuous variation of the central wavelength within a range of 760 to 840 nm with a spectral width of 25 nm (Fig. 4). Pulse energy and pulse stability (rms/peak-to-peak) of individual spectral slices are almost independent of the central wavelength as depicted in table 2.

Table 2. Ti:sapphire stability for individual spectral slices

λ central[nm]	785	805	835	805
bandwidth [nm]	25	25	25	90
stability [%,rms]	0.39	0.36	0.39	0.35
stability [%,P2P]	2.2	2	1.7	2.8
duration [min]	2	2	2	2
pulse energy [mJ]	18.2	18	17.9	18.2

Wavelength-tunability could also be demonstrated for the second harmonic (Fig. 5). We achieved conversion efficiencies of typically 15-20% with a bandwidth of up to 10 nm (FWHM). The resulting SHG pulse energies were 2.7 – 3.2 mJ. Preliminary results show, that UV pulse energies of up to 500 µJ seems feasible by keeping a bandwidth of 2-3 nm. Such a bandwidth is sufficient for efficient UV pulse shaping and stretching.

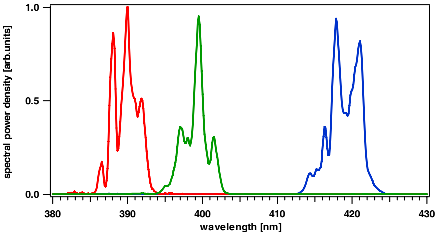

Figure 5: Demonstration of wavelength-tunable second-harmonic generation at a high power level

UV Pulse Shaping

The spatial and temporal shape of the amplified laser pulse is nominally Gaussian. Electron beam dynamics simulations indicate, that a flattop-like pulse shape helps to generate uniform temporal and spatial electron distribution resulting in a lower transverse emittance at the gun. Since other simulations show that a gaussian-like electron distribution is less sensitive to timing jitter in the undulator it is more likely that an intermediate pulse shape will be optimal for best FEL performance [10]. Therefore powerful pulse shaping tools are required.

The formation of arbitrary shaped UV pulses, however, is non trivial. In the past, indirect techniques have been applied such as frequency-domain pulse shaping at the fundamental wavelength (near IR) due to the lack of appropriate shaping tools in the UV. The shape is then distorted during the conversion process to UV, because of nonlinear effects.

Our approach for achieving high-quality and arbitrarily shaped UV pulses is based on *direct* UV pulse stretching and shaping. This became possible very recently thanks to the availability of an efficient acousto-optical pulse shaper working in the UV (UV-Dazzler, Fastlite Inc.). This device allows efficient phase and amplitude control in the wavelength range of 250-400 nm. With a resolution of 0.1 nm and a deflection efficiency of up to 40 % at 250 nm the UV Dazzler should allow the formation of powerful arbitrarily shaped UV pulses. To avoid intensity-induced nonlinear absorption the UV Dazzler is seeded with UV pulses stretched to several ps. For temporal pulse stretching we designed a dedicated prism assembly shown in Fig. 6.

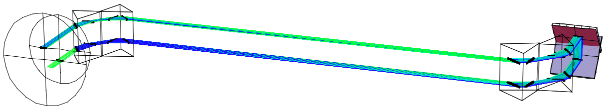

Figure 6: UV pulse strecher based on a double-prism sequence.

Efficient pulse stretching in the UV is challenging since gratings, which are commonly used for pulse stretchers in the near-IR, suffer from high losses in this wavelength range. In fact, the expected energy throughput of a grating-based stretcher would be <25%. A prism-based design seems more promising. Various glass substrates from different suppliers have been tested at PSI in order to optimize the energy through-put by minimizing intensity-induced two-photon absorption but still offering a large angular dispersion to keep the geometrical dimensions of the stretcher small.

A prototype double-prism stretcher is currently being built at PSI based on Corning 7980 HPFS glass substrates. Ray-tracing calculations indicate that a distance of 3 m is required to stretch the UV pulse from ≈100 fs to the required 10 ps. The expected energy throughput should be close to 60%. The pulse length can be continuously varied within 2-10 ps by adapting the geometrical distance between the two prism pairs.

We expect the UV-Dazzler UV-stretcher combination to provide the requested UV pulse quality together with arbitrarily temporal pulse shaping . Temporal pulse characterization will be performed by cross-correlation with the fundamental laser pulse.

ND:YLF LASER SYSTEM

The second laser system used for photoemission is a compact (60x90x30cm^3), turn-key Nd:YLF amplifier. It is currently used to drive the 4 MeV diode / RF gun assembly at PSI [5]. This laser system is a commercial product (TimeBandwidth Products, Swizterland) which has been adapted to the stability requirements of FEL electron guns.

The laser consists of an oscillator running at 83.275 MHz (18th sub-harmonic of master clock) delivering 190 mW at 1048 nm. Subsequent amplification in a regenerative amplifier yields 2.2 mJ, 10.4 ps pulses (FWHM) (Fig. 1). Optionally the pulse duration can be increased up to 33 ps (FWHM) by a spectral filter located in the oscillator cavity. Sequential frequency doubling in a 3mm and 2 mm BBO crystal, respectively, provides typically 250 uJ pulse energy at 262 nm. Transverse pulse

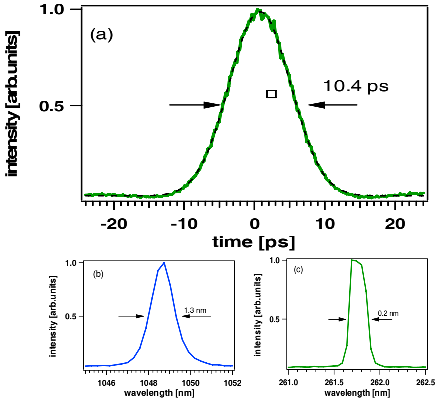

Figure 7: (a) Intensity autocorrelation of fundamental pulse. (b) corresponding fundamental spectrum. (c) spectrum after quadrupling in two BBO cyrstals.

shaping is performed by expanding the Gaussian-like intensity profile transversely and selecting the central part (≈30%) with an aperture mask. A lens is used to image the profile at the mask position onto the cathode. A de-magnification factor of 2.5 is applied in order to improve beam pointing stability on the cathode, located 12 m apart from the spatial mask. An evacuated transfer line helps to improve the laser beam pointing stability at the cathode by an order of magnitude to < 3 µm (rms).

Synchronization to the 1.49 GHz master clock signal is performed by a CLX1100 (TimeBandwidthProducts Inc.). It measures the phase/frequency offset between the laser pulse and the reference clock signal and subsequently adjusts the cavity length of the optical oscillator to maintain a constant relation between the two signals. A long-term phase jitter measurement recorded over 42 hours is presented in table 3. The results show that 99.9% of the laser shots suffer from a jitter smaller than 0.1 ps. Presently no time jitter measurements have been performed at the cathode level after the transfer line.

Table 3. Timing jitter between RF master clock and optical oscillator

jitter [ps]	#shots	ratio
<0.05	1518020	0.9991
0.05...0.1	1270	8.36E-04
0.1...0.15	32	2.11E-05
0.15...0.2	15	9.87E-06
0.2...0.3	10	6.58E-06
0.3...0.4	9	5.92E-06
0.4...0.5	4	2.63E-06
0.5...0.7	3	1.97E-06

The design of the laser has been optimized to cover the high stability requirements for the electron production. Shot-to-shot fluctuations in high-power amplifiers are mostly dominated by the noise level of the pump laser. Therefore a low-noise quasi CW laser diode emitting at 797 nm has been chosen to pump the regenerative amplifier sideways. This provides an exceptional pulse-to-pulse stability of 0.1% (rms) in the IR and typically <0.4% (rms) for the quadrupled pulse at 262 nm, respectively.

A series of small modifications helped furthermore to improve the laser stability. Heat-producing devices, such as diode drivers, have been placed outside the optical system to avoid detrimental air convection flow in the laser cavities. Heat-producing devices inside the laser box (such as Medox Pockels cell, crystal mounts) are thermally isolated from the laser breadboard by Teflon plates and are water cooled to provide heat dissipation. To improve mechanical stability, non-adjustable mirror mounts were used whenever possible. An additional home-built water-cooled box provides improved temperature stability (+/- 0.1 °C) in the vicinity of the laser system.

The turn-key mode, low maintenance intervals and a remarkable laser stability makes the Nd:YLF laser ideally suited for the PSI diode / RF gun test facility. The lack of arbitrarily temporal pulse shaping, however, may turn out as a severe drawback to generate low-emittance electron beam.

SUMMARY AND OUTLOOK

We presented the design and performance of two different gun lasers currently commissioned at PSI. The sophisticated Ti:sapphire laser system offers wavelength tunability and pulse shaping in the UV which should help to produce a low emittance electron beam at the gun. Future upgrades will involve an extension of wavelength tunability to 250-300 nm at an increased energy stability. The second gun laser is a compact Nd:YLF amplifier currently used as workhorse to drive the diode / RF gun test facility at PSI.

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