

NEW CONCEPT FOR THE SwissFEL GUN LASER

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Abstract

We report on a new concept for the gun laser system of the future hard and soft x-ray SASE FEL (SwissFEL) at the Paul Scherrer Institute and present first experimental verifications. The system consists of a hybrid Yb fiber and solid state Yb:CaF₂ amplifier. The laser performance, such as energy stability, timing jitter, double pulse operation, temporal and spatial pulse shape of the ultra-violet laser pulses match the SwissFEL requirements. The mature and stable direct diode pumping technology and an optimized design allow for high reliability, long lifetime and lower maintenance cost compared to the widely used Ti:sapphire laser systems.

INTRODUCTION

The operation of SwissFEL puts very stringent constraints on the gun laser system. First the parameters, such as energy stability, timing jitter, double pulse operation, flat top temporal and spatial pulse shape of the ultra-violet (UV) laser pulses (see Tab. 1) used to generate the photo-electrons are challenging even for the state of the art laser technologies.

Table 1: Gun Laser Characteristics for SwissFEL

Laser specifications	
Maximum pulse energy on cathode	60 μ J
Central wavelength	250-300 nm
Bandwidth (FWHM)	1-2 nm
Pulse repetition rate	100 Hz
Double-pulse operation	yes
Delay between double pulses	50 ns
Laser spot size on cathode (rms) (10 pC/200 pC)	0.1 / 0.27 mm
Minimum pulse rise-time	< 0.7 ps
Pulse duration (FWHM)	3-10 ps
Longitudinal intensity profile	various
Transverse intensity profile	Uniform
Laser-to-RF phase jitter on cathode (rms)	<100 fs
UV pulse energy fluctuation	<0.5% rms
Pointing stability on cathode (relative to laser diameter)	<1% ptp

Second, the laser system must be extremely stable, reliable and its maintenance cost as low as possible. In this perspective, we prospected for alternative technologies to the well known, commonly used but costly Ti:sapphire (Ti:Sa) laser systems [1]. Here we show that a hybrid Yb fiber and solid state Yb:CaF₂ amplifier system can be a very interesting approach. This gain medium [2] allows the production of sub-500 fs, high fidelity, high stability, high energy pulses in the infrared and in the ultra-violet with low timing jitter. The system profits of the mature, stable direct diode pumping technology and optimized design. It delivers the two high-energy, shaped UV pulses separated by 28 ns to produce the photo-electrons, a short IR probe (<80 fs FWHM) to temporally characterize those pulses and the two stretched IR pulses (50 ps FWHM) necessary for the laser heater.

LASER SYSTEM

The choice of the laser system gain medium and architecture has a direct impact on its final performance and reliability. The Yb:CaF₂ have all desired properties for the production of high energy, UV femtosecond pulses. Moreover by keeping the laser architecture simple and compact the system reliability is improved.

Yb:CaF₂ Crystal

The use of calcium fluoride with ytterbium doping (Yb:CaF₂) as an active laser medium for CW systems started in 2004 [3]. Its very interesting properties for laser amplification led to developments for short-pulse, high energy laser system up to the TW-scale [4].

- Yb:CaF₂ crystal exhibit a very broad and smooth emission band. The material is able to emit in the 1020-1060 nm spectral range allowing the generation of sub-500 fs pulses.
- The crystal absorption cross section exhibits a pronounced and narrow band peak at 980 nm as can be seen in figure 1. This point is of particular interest since it allows direct pumping with CW infrared diode modules developed for telecom applications.
- The material fluorescence lifetime of 2.4 ms and the thermal conductivity of 4.9 W.m⁻¹.K⁻¹ are well suited to the design of high power lasers. The first one is crucial, since it permits high energy storage in regenerative amplifier cavities leading to high energy pulses. The later permits CW pumping with high average power while avoiding detrimental thermal effects.

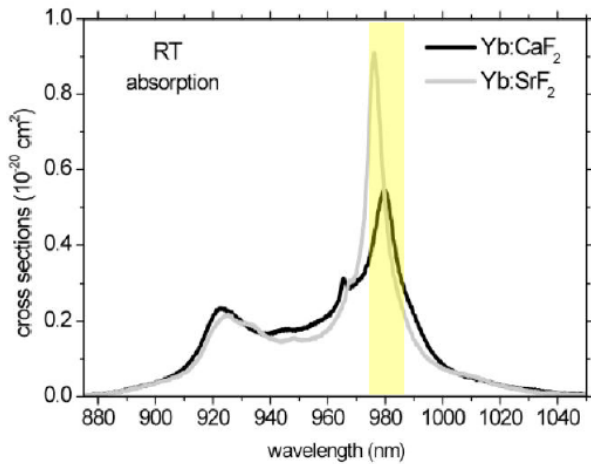


Figure 1: Absorption spectrum of Yb:CaF₂ at RT. The absorption peak around 980 nm (yellow window) allows direct pumping with CW diode. The figure is extracted from Ref. [2].

Laser System Layout

The future SwissFEL gun laser is a complex laser system. Apart from stringent specifications in terms of pulse energy, temporal profile and timing jitter, it needs to deliver three pulses with very different properties:

- A picosecond, temporally and spatially flat top UV ($\lambda=260$ nm) pulse that generates the photo-electrons at the cathode.

- A picosecond, temporally Gaussian, infrared pulse ($\lambda=1040$ nm) for the laser heater.
- A sub-50 fs temporally Gaussian, infrared pulse ($\lambda=1040$ nm) used as a short probe in order to characterize temporally the UV pulse via optical cross-correlation.

The schematic of our Yb:CaF₂ CPA system is shown in Fig. 2. The oscillator delivers broadband pulses at 71.4 MHz and is used as seed for the 100 Hz amplifier. Up to now, our choice for the oscillator will be the Origami-10 (OneFive). The reason for this is the exceptionally low timing jitter of the device when synchronized to the master timing system. The specific associated synchronization electronics have been developed by the PSI Timing and Synchronization group. This results in an integrated jitter noise that is <35 fs RMS over 10Hz-1MHz and <10 fs RMS over 1kHz-10MHz [5].

After stretching, the oscillator output is amplified in a regenerative amplifier up 5 mJ energy before compression. Thanks to the above mentioned properties of the Yb:CaF₂ medium, it is possible to reach this high level of energy in a single amplifier stage. The regenerative amplifier ensures a very high output mode quality and energy stability. Moreover all the components (stretcher, amplifier and compressor) are packaged in a thermally stabilized and very compact single box as can be seen in Fig. 3. This ensures a high mechanical stability of the system and also low sensitivity to environmental changes.

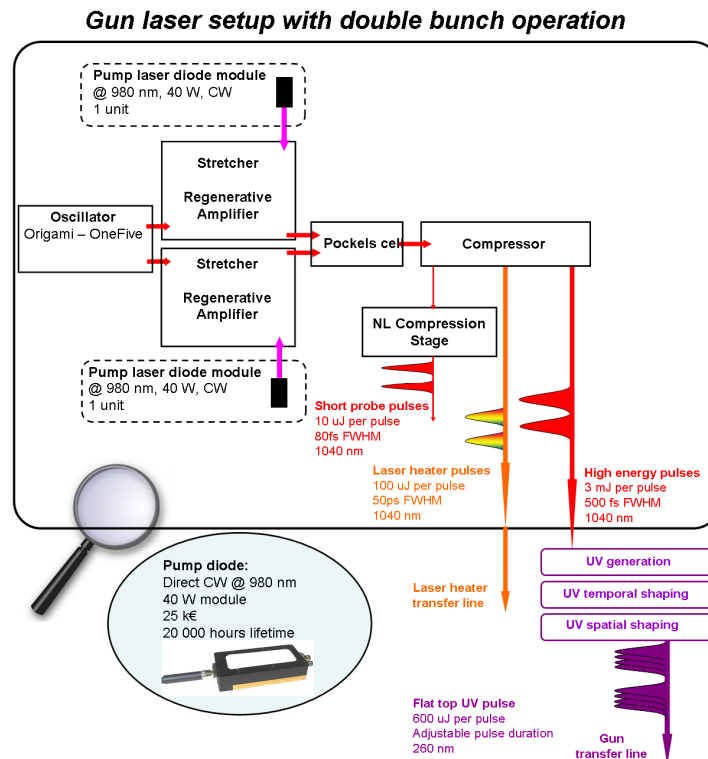


Figure 2: Schematic of the Yb:CaF₂ CPA system. The system is able to deliver the temporally shaped UV pulses to the gun cathode but also the laser heater pulse and a short probe for UV pulse diagnostic. The system is able to deliver 2 pulses delayed by 28 ns in order to seed the hard and soft X-ray line of the FEL.

The regenerative amplifier is pumped with a single module of CW diode delivering high power at 980 nm. As depicted in Fig. 1. This pumping scheme combines several advantages: first an exceptionally high pumping efficiency since the material can be pumped with the fundamental radiation emitted by the diode stack. Second a high reliability and a long lifetime (around 20 000 hours) of the pump laser. And finally high compactness and low maintenance cost (around 25 k€/module) with respect to the Nd:YAG technology used to pump Ti:Sa systems.

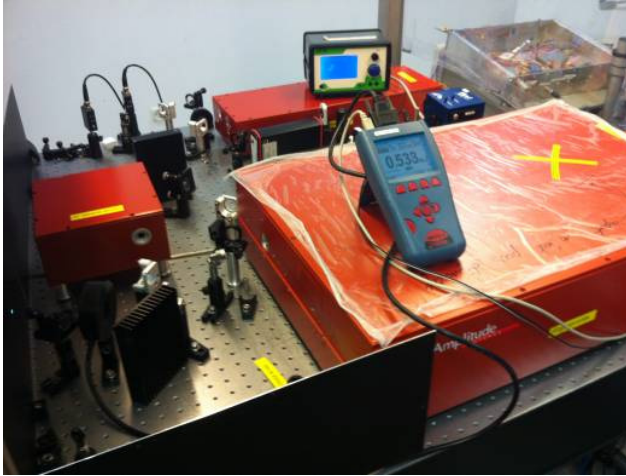


Figure 3: Picture of the prototype laser tested at Amplitude Systèmes. The various stages are packaged in sealed, temperature stabilized boxes. The amplifier size is only 50*50 cm (includes only the high energy IR pulse).

After amplification, the pulse is compressed to 500 fs FWHM duration with a transmission grating pulse compressor. The pulse energy is around 3 mJ. Afterwards, a properly designed frequency conversion stage produces 800 μ J at 260 nm. Subsequent UV temporal and spatial shaping consisting in respectively, pulse stacking and aperture clipping enables to generate 500 μ J, temporally and spatially flat-top UV pulse.

The system is also able to deliver the laser heater pulse. A pickup on the main IR beam and a dedicated compressor give the 50 ps FWHM stretched pulses carrying an energy of 100 μ J. No temporal shaping is needed, the pulse temporal shape is Gaussian like. Finally, in order to characterize the flat-top UV pulse, the system also provides a short IR probe pulse. A non-linear compression stage will be used to provide sub-80 fs FWHM pulses with a moderate energy of 10 μ J.

Moreover, the system must be able to deliver 2 pulses separated by a delay of 28 ns in order to seed the hard and soft X-ray line of the FEL. This requirement is fulfilled by simply adding a second CPA system seeded with the same oscillator as shown in Fig. 2. The twin amplifier architecture increases the system flexibility with regards of the FEL operation and ensures a backup system in case

of component failure. In order to improve our knowledge whether such a system is feasible, we performed some performance tests on a laser prototype manufactured by the company Amplitude Systèmes (Pessac-France). The following paragraphs show the measurement results.

Energy Stability

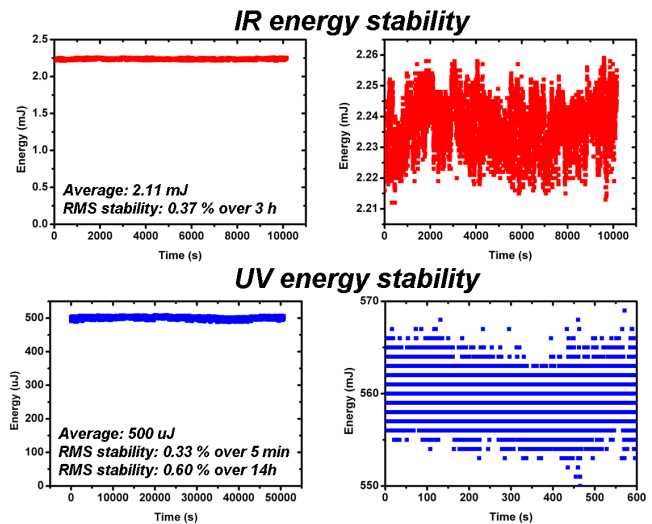


Figure 4: Measured laser energy and stability in the IR and in the UV part. The system exhibits a very high stability of 0.33 % RMS over 5 minutes and 0.6 % RMS over 14 hours with an average UV output of 500 μ J.

The system energy output was monitored both in the IR and in the UV output. As discussed above, the CW pumping scheme and the saturation of the regenerative amplifier allow reaching very high energy stability. As shown in Fig. 4, the average IR output energy was 2.11 mJ with an RMS stability of 0.37% over 3 hours. The averaged energy in the UV was 500 μ J. Moreover, both long term (over 14 hours) and short term (over 5 minutes) stability exhibit energy fluctuations of less than 0.6% RMS. These performances fulfil well the SwissFEL gun laser of less than 1% RMS.

UV Pulse Temporal Shaping

In order to produce the desired flat-top temporal profile of the UV pulse used to generate the photo-electrons, we apply temporal shaping in the time domain [6]. The technique consists of stacking individual replicas of orthogonally polarized pulses. The replicas are produced with a set of α -BBO crystals oriented at a correct angle in order to obtain the flat top shape. We performed a test with a crystal set allowing the generation of a flat-top pulse of 7.9 ps FWHM. Figure 5 show the measured temporal profiles for 2, 4, 8 and 16 stacked replicas. The finally obtained pulse profile (Fig. 5, bottom, right hand side) is flat-top like with modulation depth on the plateau less than 20% peak-peak.

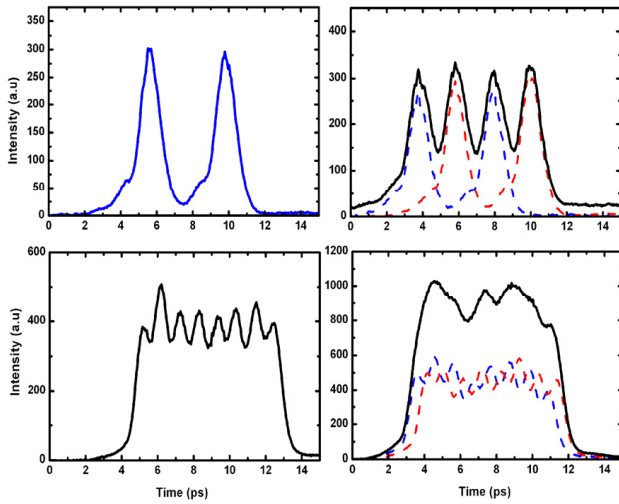


Figure 5: Measured UV pulse temporal profile. The stacking of 2, 4, 8 and 16 pulse replicas allows the generation of flat-top like UV pulse of 7.9 ps FWHM duration.

UV Spatial Shaping

In order to produce a low emittance electron beam, the gun laser must have a spatially flat-top intensity profile on the cathode plane. This is a very challenging issue, especially in the UV where both the non-linear conversion stages used to generate the UV radiation and the transport of the laser from the gun laser table down to the cathode introduce distortions and high-frequency modulations on the UV beam profile. In order to get a shaped

and smooth beam profile after the transport, a possibility is to use aperture clipping in conjunction with Fourier filtering of the beam [5]. However this technique is very inefficient in terms of energy throughput ($\approx 10\%$). In order to evaluate the quality of the UV beam delivered by the prototype and to mimic its evolution through the spatial shaping process and transport line, we built the experimental setup shown in Fig. 6. After the fourth harmonic generation module (FHG), the beam is expanded with a 2 singlet lenses telescope.

A circular aperture of 4 mm diameter is used to clip the central part of the beam in order to obtain a truncated gaussian beam profile. Finally, imaging of the aperture plane onto a virtual cathode plane is done with an imaging lens and a 10 m long optical path in air (the experimental conditions did not allow for the installation of a vacuum line). The IR and UV beam profile were recorded with a CCD camera (WinCamD) and a K6 scintillator (Metrolux) for the UV. Figure 6 shows the measured beam profiles at the laser output (left), after the FHG module in the UV (center) and after the aperture clipping (right). After the aperture, the truncated beam has a very good flat-top like profile. The modulation depth is less than 15% peak-peak. Moreover, the energy after the aperture (350 μJ) is by far enough to produce the nominal electron charge required for FEL operation. Additionally, the measurement of beam profile on the virtual cathode plane indicates that it is possible to transport the beam without significant distortion. The measured beam pointing stability is also very good taking into account that the transport was done in air, not in vacuum.

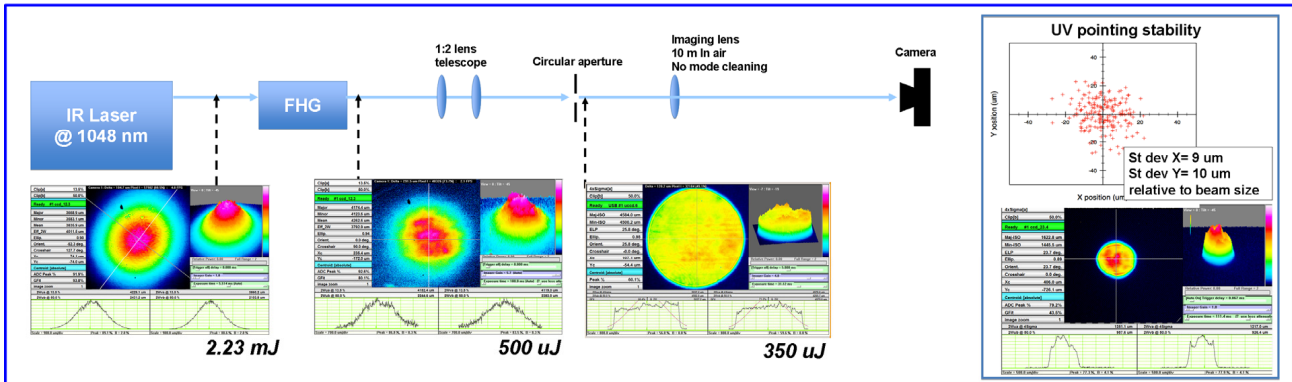


Figure 6: Schematic of the setup used to evaluate the quality of the UV beam through the spatial shaping process and transport. The beam profile was recorded at various strategic points. After the transport, a beam pointing measurement was performed as well.

CONCLUSION

We present a new concept for the future photo-injector laser system for the SwissFEL at Paul Scherrer Institute (PSI). The source is based on Yb:CaF₂ amplifier technology directly pumped by CW diodes. It profits from single stage regenerative amplifier, high fidelity packaging, direct pumping of the active material and compactness. The first experimental results presented here show that it is a valid alternative to standard Ti:Sa systems. Energy level, energy stability, UV temporal pulse shaping and transverse beam shaping match the specifications of the SwissFEL gun. Moreover, the maintenance cost of such laser is much lower than a comparable Ti:Sa based laser system.

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