DRIVE LASERS FOR PHOTOINJECTORS*

Ingo Will#, Guido Klemz
Max-Born-Institute Berlin, Germany

Abstract

This paper gives an overview of the various photocathode laser concepts that are presently used to drive the photo injectors of linacs and FEL installations. The requirements for the drive lasers are strongly determined by the properties of the photocathode of the injector; in particular by its quantum efficiency. We subdivide the exisiting photocathode lasers into four main groups depending on the laser materials used. The capabilities and limitations of the drive lasers of these four groups are categorized by average power, pulse duration and shape, as well as by the generation of macropulses.

PHOTOCATHODES WIDELY USED

Drive lasers for photo injectors are a relatively small, but important component of linacs. In the typical setup sketched in Fig. 1, such a laser usually contains an oscillator for generation of the initial pulses, an optional pulse shaper, and an amplifier. The infrared pulses are subsequently converted to green or ultraviolet light by nonlinear optical crystals, depending on the working function of the photocathode used. Finally, the pulses from the photocathode laser are imaged onto the photocathode located in the photo injector (an RF or CW gun). This leads to the generation of high-density electron bunches by photoemission, which are accelerated in the electric field of the injector as well as in the acceleration modules of the linac. Charge, duration (length), shape, emittance and timing of the generated electron bunches can be controlled by appropriately tuning the parameters of the laser pulses.

Table 1 gives an overview of the three most common photocathode materials that are currently being used. A much more comprehensive compilation of photocathode materials can be found in [1]. The particularly important parameters of the photocathodes are the desired laser wavelength and the quantum efficiency (QE).

- Metallic photocathodes are very robust and easy to use. They are often a good choice for photoinjectors with low average beam current. They require high laser pulse energy and power due to their low quantum efficiency. For copper with a quantum efficiency of the order of 10^{-5} to 10^{-4}, an average laser power of 50 to 500 W in the UV is needed for 1 mA average beam current. This exceeds the power that presently existing lasers can deliver in green light. That is why more efficient photocathode materials are required for high-current injectors.
- Cesium Telluride (Cs_2Te) is a relatively robust material and is therefore used in many RF guns. It has an initial QE of several percent, that drops during running time in the photoinjector to ~1 %. This corresponds to 0.5 mJ/nC laser pulse energy and to 0.5 W/mA laser power. Such photocathodes require UV light ($\lambda \sim 0.26\ \mu m$) for their operation. To achieve this wavelength, one has to convert the infrared radiation of the laser to its third or fourth harmonic by using nonlinear crystals. This unfavourable conversion process strongly limits the pulse energy available from the laser.
- Gallium Arsenide (GaAs) photocathodes do not exhibit this disadvantage, since they can be operated with green light ($\lambda \sim 0.53\ \mu m$). Their quantum efficiency is larger than that of Cs_2Te. Thus, relatively compact lasers can be used for generation of high beam current. An obvious disadvantage of GaAs cathodes is their need for a very high vacuum. In most applications, periodic regeneration (cesiation) of the cathode is required at intervals between one day and one week. These photocathodes are typically employed in photoinjectors with very high average beam current (I >>1 mA).

The laser power and energy required from the laser system can in practice be up to one order of magnitude higher than the photocathode requirements given above. The additional laser power is needed to compensate for losses in the optical beamline (e.g. at beam-shaping apertures), for ageing of the cathode, as well as for ageing of optical elements of the laser.

Table 1: Comparison of the three most widely used materials for photocathodes.

	Cu	**Cs_2Te**	**GaAs**
Laser wavelength	0.26 µm	0.26 µm	0.53 µm 0.75 µm
Quantum efficiency	10^{-4}...10^{-6}	~1%	1...10%
Laser pulse energy and power needed	50…500 µJ/nC 50…500 W/mA	0.5 µJ/nC 0.5 W/mA	0.02…0.2 µJ/nC 0.02…0.2 W/mA
used at:	SPARC, Fermilab, LCLS (SLAC)	FLASH, PITZ, ELBE, CTF/CLIC, Fermilab, SLAC	JLAB, CEBAF, 4GLS

* This project is supported by the German Ministry of Education and Science, contract no. 05ES4MB1/1.
#will@mbi-berlin.de

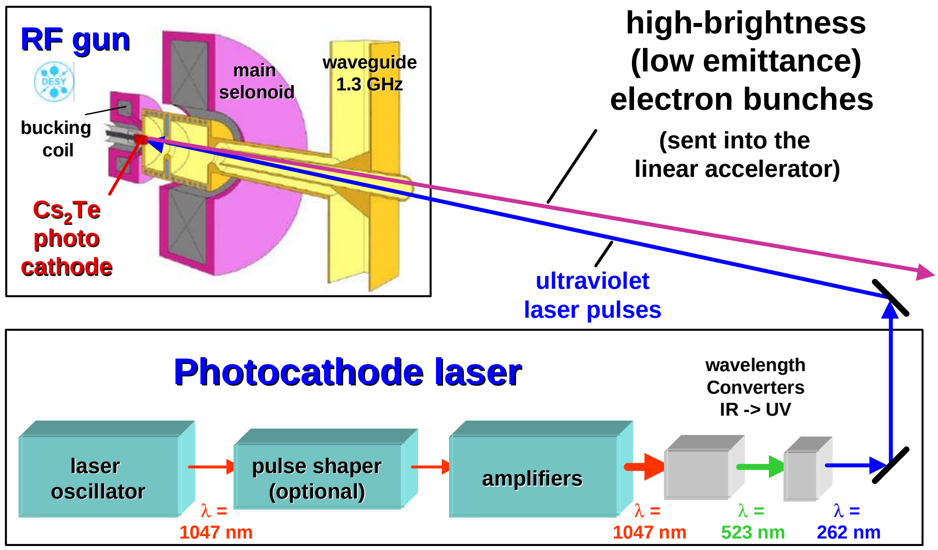

Figure 1: General setup of a photoinjector
(picture of the gun by courtesy of K. Floettmann, DESY Hamburg)

DRIVE LASERS

The properties of the photocathode have a particularly strong influence on the desired laser energy and its wavelength. Most lasers that are presently used to generate pulses of this energy and power belong to one of the following four classes:

- Picosecond Neodymium-doped lasers (Nd:YLF, Nd:YVO4, Nd:YAG) generating both single pulses and pulse trains (macropulses);
- Femtosecond Titanium Sapphire (Ti:Sa) lasers for shorter pulses and for generation of shaped pulses;
- Lasers based on Ytterbium-doped materials (Yb:YAG, Yb:KGW, Yb:glass Fibre lasers), which have recently been made possible by the availability of high-brightness pump diodes;
- Fibre lasers, a new emerging technology which promises reliable compact systems, but are presently restricted to low pulse-energy applications.

The advantages and limits of these lasers are discussed in the following sections.

Lasers with Neodymium-doped crystals

Neodymium-doped laser crystals, such as Nd:YAG, Nd:YLF and Nd:YVO_4, are widely used in lasers delivering picosecond pulses. Although flashlamp-pumped amplifiers are still being used in high-power laser installations, most systems today employ semiconductor diodes as pump sources. These diode-pumped lasers typically reach a stability of 1 % or better.

Modelocked Nd:YLF and Nd:YVO_4 lasers can deliver an average power up to ~ 40 W in the IR (λ = 1.05 µm and 1.06 µm resp.) and > 20 W in green light. With GaAs photocathodes, this should allow for generation of high average beam curent (> 10 mA). When converted to the fourth harmonic (UV, λ = 0.26 µm) as required for Cs_2Te photocathodes, the average power is limited to ~1 W due to thermal effects in the frequency conversion crystal. This power in the UV spectral range should be sufficient for producing ~1 mA average beam current in a superconducting RF gun [2].

Due to the high efficiency, good reliability, relatively simple setup and low maintenance costs, lasers based on Nd-doped laser materials are being used in many laboratories, e.g. FLASH, Daresbury, PITZ, FZD (Rossendorf), CLIC/CTF, Fermilab, SLAC.

Lasers utilizing Nd-doped crystals can generate both single pulses and pulse trains (macropulses). An example of a laser generating long macropulses is the photocathode laser of the FLASH facility at DESY that was also developed at the MBI [3,4]. As is shown in Fig. 3, this laser is able to produce trains (macropulses) with the specific pulse structure suitable for a superconducting linac of the TESLA type.

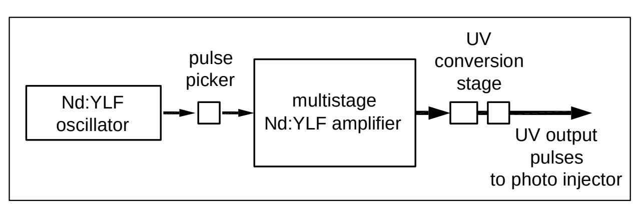

Figure 2: Basic scheme of the Nd:YLF photoinjector drive laser used at FLASH and PITZ

The ability of these lasers to produce shaped picosecond pulses was demonstrated by inserting a pulse shaper between the oscillator and the amplifier chain of the photocathode laser at PITZ. The result for generation of flat-top pulses is depicted in Fig. 4.

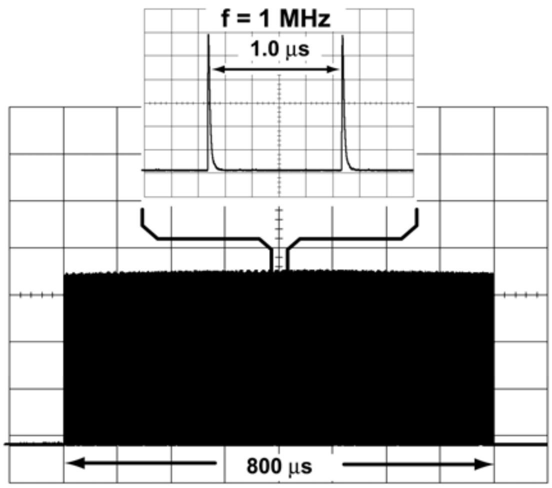

Figure 3: Output pulse train of the Nd:YLF drive laser

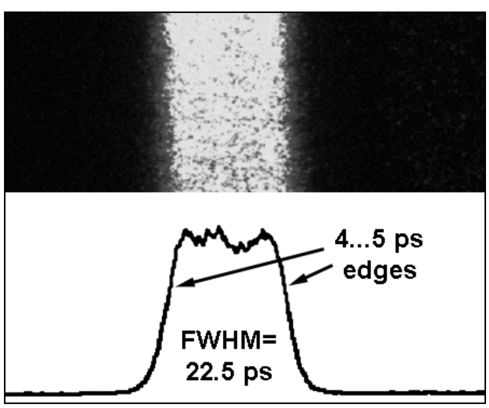

Figure 4: Streak camera record of the pulse shape at the Nd:YLF drive laser in use at PITZ

The pulses produced exhibit a flat-top pulse of ~ 22.5 ps duration. Unfortunately, the shortest edges that could be realized still had a duration of ~ 5 ps after conversion to the UV, which is 2...3 times longer than the requirement. This shows that the ability of lasers based on Nd-doped crystals is limited for picosecond pulses due to the limited fluorescence bandwidth of these laser materials. In order to overcome this restriction, a laser medium with larger fluorescence bandwidth has to be used.

Titanium Sapphire lasers

A laser medium with the largest fluorescence bandwidth available today is Titanium sapphire (Ti:Sa), which is commonly used for generation of femtosecond pulses. This laser medium is applied in several accelerator labs for generation of shaped pulses with sharp rising and falling edges. As the work conducted at SPARC and at SPring-8 show, Ti:Sa lasers offer remarkable pulse-shaping capabilities. Flat-top pulses of ~ 10 ps duration, with edges of 1 ps duration, have been generated in both laboratories [5,6].

The maximum average power that can currently be produced by Ti:Sa lasers is approximately > 10 W. This is reached with cryogenic cooling of the Ti:Sa crystal.

At present, Ti:Sa lasers are only suitable for generating single pulses. There are no demonstrated solutions to enable a Ti:Sa laser to generate trains (macropulses) with a pulse energy appropriate for driving a photo injector. The reason for this is the short excited-state lifetime of 3.2 μs and the lack of pump lasers that must generate pulses of several tens or hundreds of microseconds duration, depending on the length of the macropulse to be produced.

Lasers based on Ytterbium-doped materials

Ytterbium-doped crystals, such as Yb:YAG, Yb:KGW, Yb:KYW and $Yb:CaF_2$, are another class of laser media with a bandwidth sufficient for generation of femtosecond pulses. These materials must be pumped by high-brightness laser diodes that became available in the past decade. Crystals doped with Yb are used for generating the highest average power available. Several hundred watts can be reached with the so-called Yb:YAG thin-disk laser geometry [7,8].

Due to the long excited-state lifetime, which is between several hundred microseconds and several milliseconds, these materials are well suited for generation of pulse trains or macropulses. A certain disadvantage is their low cross section for stimulated emission, which has to be compensated in practice by using special laser geometries such as regenerative or multipass amplifiers.

Figure 5 shows a scheme of a laser system being developed at the MBI that generates trains of flat-top pulses for FLASH. It is based on Yb:KGW and Yb:YAG. In order to compensate for the low gain of Yb-doped crystals, this laser system comprises two regenerative amplifiers arranged before and after the pulse shaper. These pulse trains can contain up to 1000 micropulses that are spaced by 1 μs, with > 20 μJ energy each.

Insertion of an appropriate pulse shaper facilitates the generation of flat-top pulses. We measure the picsosecond pulse shape of this setup by a cross-correlation method [9]. Our results obtained with a direct-space-to-time (DST) [10] pulse shaper are shown in Fig. 6. The shaped pulses have ~18 ps FWHM, with duration of the edges between 1.8 and 2 ps. Work is ongoing to further increase the pulse energy by optimizing the final amplifier.

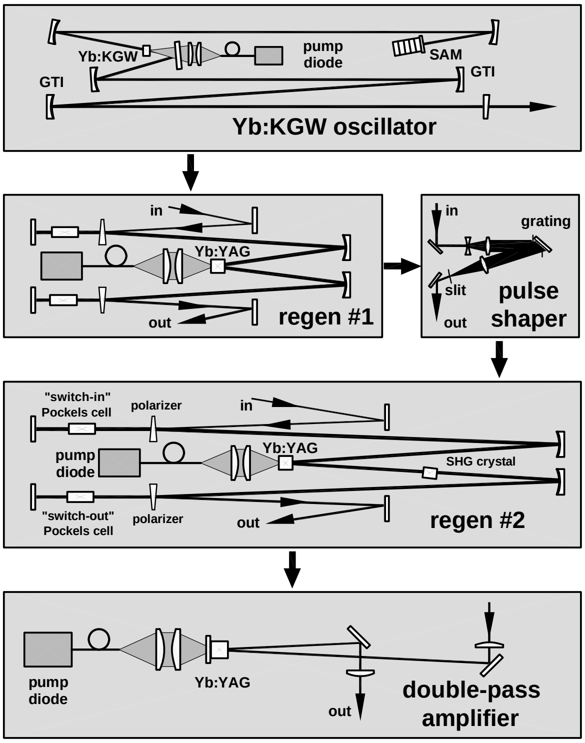

Figure 5: Scheme of the experimental Yb:YAG laser-driver laser under development at the MBI

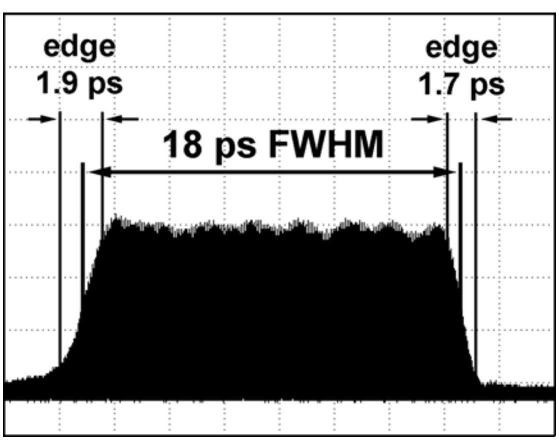

Figure 6: Cross correlation signal showing the flat-top pulse shape of the experimental Yb:YAG laser

Fibre lasers

Fibre lasers represent an upcoming technology for a compact, potentially highly stable class of mode-locked lasers at MHz repetition rates. Ytterbium-doped fibres provide a large fluorescence bandwidth sufficient to allow for subpicosecond pulses. The beam diameter within the fibre is limited to several tens of micrometers. Thus the pulse energies are relatively low, typically in the nJ-range. The average output power of mode-locked fibre oscillators is currently limited to ~ 0.2 W [11]; i.e., it is one to two orders of magnitude below that of standard crystal oscillators.

Lanthanide-doped fibres have a high gain that scales with the length of the fibre. The pulse energy can be increased up to three orders of magnitude using chirped-pulse amplification [12,13]. However, the resulting amplified pulses are not bandwidth-limited. Strong pedestal or double/triple pulses may occur [14,15]. Therefore it is difficult to convert the infrared pulse into the UV. In addition, generation of shaped picosecond pulses with fibre lasers will require novel and demanding concepts. Therefore, fibre lasers are presently well-suited for photoinjectors with GaAs cathodes that are operated with a small bunch charge. At high repetition rates, a beam current up to 10 mA can be reached [16,17].

SUMMARY

Solid-state lasers driving the RF gun are a relatively small, but important component of the linacs. The parameters of the laser pulses are strongly determined by the material of the photocathode and its quantum efficiency. Conversely, the laser pulses have a strong impact on crucial parameters of the electron bunches generated; in particular on bunch length (duration), bunch shape, timing and emittance. Very stable operation of such lasers is generally required for use as a photocathode drive laser. A pulse energy stability of 1 % can be reached today by using semiconductor diodes as pump sources for the laser.

The available average power in the UV is limited by the frequency conversion crystals to ~ 1 W. In order to increase the average beam current above ~ 1 mA as obtained by a Cs_2Te photocathode at such a power level, GaAs photocathodes with high QE have to be applied. They offer the advantage of operation with green light.

The properties of the laser media discussed here can be summarized as follows:

- Lasers based on Nd-doped materials are commonly applied as photocathode lasers in many labs due to their efficiency, compactness and reliability. They are well suited for generation of picosecond pulses with $\sigma > 4$ ps duration, and they are efficient and very stable when pumped by semiconductor diodes. Lasers for the generation of both single pulses and macropulses have been developed. The fluorescence bandwidth of Nd-lasers is insufficiently low for generation of flat-top pulses with sharp rising and falling edges.
- Ti:Sa lasers offer remarkable possibilities for pulse shaping. In particular, they are well suited for generation of flat-top pulses of the desired edge steepness. Otherwise, they require a significant effort in maintenance. They are presently only capable of generating single or low repetition rate pulses at the

pulse energies required for photoinjectors. No laser for generating suitably high energy pulse trains (macropulses) exists at present.

- Lasers based on Yb-doped materials can be directly pumped by semiconductor diodes and do not need the expensive pump lasers used in Ti:Sa systems. They offer good pulse-shaping capabilities and reach the highest average laser power available today with the so-called thin-disk geometry. These lasers are also capable of delivering pulse trains (macropulses) at relatively low energy. Dedicated amplifiers to further boost this pulse energy are under development.
- Fibre lasers are a new upcoming type of very compact and easy-to-use laser. The pulse energy is limited due to the small beam diameter in the fibre. Therefore the use of fibre lasers is presently restricted to photoinjectors with GaAs photocathodes This material has a high quantum efficiency and can be driven with green light pulses.

It turns out that there is no "universal" laser type at present that would be suitable for all, or at least for a broad class of injectors. In practice, the drive laser emerges as a very special component of the electron source. Its type and its design have to be carefully chosen with regards to the pulse parameters required by the photoinjector and the linac.

REFERENCES

[1] J. Teichert, R. Xiang, G. Suberlucq, J.W.J. Verschuur, “Report on photocathodes”, CARE Note-2004-033-PHIN, http://esgard.lal.in2p3.fr/Project/Activities/Current/Deliverables/CARE_Deliverables.htm

[2] H. Trautner et al., “Cathodes for CTF3/CLIC”, 1st Photoinjector Workshop, CERN, September 24-25 (2001) http://photoinjector.web.cern.ch/photoinjector/Coferences/Photoinj_2001/PIwks_heiko_0901.PDF

[3] I. Will, G. Koss, I. Templin, “The upgraded photocathode laser of the TESLA Test Facility”, Nuclear Instruments and Methods in Physics Research A 541 (2005) 467

[4] Annual report of the Max Born Institute, Berlin (2006), Section 4-1, p. 81, http://www.mbi-berlin.de/en/research/annuals/ 2006/mbi_2006.pdf

[5] C. Vicario, “Laser temporal pulse shaping experiment for SPARC photoinjector”, EPAC’04, Lucerne, July 2004, p. 1300, http://www.jacow.org.

[6] C. Vicario, “Laser pulse shaping for high-brightness photoinjector”, CARE06, Frascati, November 2006, http://www.lnf.infn.it/conference/care06/TALKS/Vicario.ppt

[7] C. Stolzenburg et al., “Cavity-dumped intracavity-frequency-doubled Yb:YAG thin disk laser with 100 W average power”, Opt. Lett. 32 (2007) 1123

[8] E. Innerhofer et al., “60 W average power in 810-fs pulses from a thin-disk Yb:YAG laser”, Opt. Lett. 28 (2003) 367

[9] Annual report of the Max Born Institute, Berlin (2006), Section 1-02, pp. 43, http://www.mbi-berlin.de/en/research/annuals/ 2006/mbi_2006.pdf

[10] C. Sauteret, M. Novaro, O. Martin, “Passive pulse shaping by spectral narrowing of picosecond pulses”, Appl. Optics 20 (1981) 1487

[11] J. R. Buckley et al., “Femtosecond fiber lasers with pulse energies above 10 nJ”, Opt. Lett. 30 (2005) 1888

[12] A. Galvanauskas et al., “Generation of high-energy femtosecond pulses in multimode-core Yb-fiber chirped-pulse amplification systems”, Opt. Lett. 26 (2001) 935

[13] L. Shah et al., “Micromachining with a 50 W, 50 μJ, subpicosecond fiber laser system”, Opt. Express. 14 (2006) 12546

[14] J. Limpert et al., “High-power femtosecond Yb-doped fiber amplifier”, Opt. Express. 10 (2002) 628

[15] B. Ortaç et al., “Generation of parabolic bound pulses from a Yb-fiber laser”, Opt. Express 14 (2006) 6075

[16] A. Liu et al. “60-W green output by frequency doubling of a polarized Yb-doped fiber laser”, Opt. Lett. 30 (2005) 67

[17] M. Poelker et al., “Status of 100kV DC High Voltage Polarized Electrons Guns at CEBAF”, ERL’07, Daresbury, May 21-25 (2007)