LASER SYSTEMS FOR NEXT GENERATION LIGHT SOURCES

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Abstract

Particle accelerator and laser technologies are effectively combining with each other in the development of next generation light sources, with the latter being one of the key factors determining the ultimate performance of these machines. VUV and X-FEL facilities take advantage of laser technology at many strategic points: creation of the electron bunch (photo-injector laser), acceleration (laser heater), undulators (seed laser), beam diagnostics (electro-optic sampling lasers), user experiments (pump-probe lasers). This talk will discuss the main requirements and challenges (photoinjector and seed lasers in particular) for the laser systems and will illustrate proposed solutions and obtained results. Recent laser achievements that are likely to have impact on important developments like high average power injectors, different guns, tunable short wavelength FEL seeding will also be addressed.

INTRODUCTION

The past several years have seen a very fast proliferation of ultrafast laser technology into the FEL projects under construction and in process of preparation and submission. While in the previous decade (1989-1999) the only important laser system considered in relation to FEL has been the photo-injector laser, during the last 10 years a number of new laser systems was proposed in papers and incorporated in the submitted FEL projects. Some of the main examples are the seed laser, laser heater, pump-probe lasers, master oscillator laser, electro-optical sampling laser. We note that in addition, ultrafast lasers have been introduced also in alternative light sources like storage ring based 'slicing' and HGHG, Compton scattering, etc. In this paper we will concentrate only on some of the FEL related lasers listed above, namely photoinjector and seed, however we note that many requirements and therefore laser technology solutions that will be discussed here are applicable for a broader group of light sources. Presenting an overview of the lasers implemented in all possible FEL schemes considered in the literature goes beyond the scope of this paper. We would rather try to start from the generally accepted main parameters for ongoing projects and review the state of the art laser technology solutions at disposal now and those that could be expected in a few years time. The trends will be analysed from the point of view of the laser technology, rather than from accelerator point of view.

Below we will separately address some of the important points related to the photoinjector and seed lasers which are at present the most demanding systems among the above listed FEL lasers.

PHOTOINJECTOR LASER

The photoinjector laser (PIL) is a key element in all FEL designs. The pulse and beam quality of this system is of crucial importance for the overall FEL performance, as it is directly imprinted on the quality of the generated electron bunch. It is now well accepted, that both temporal and spatial shaping of the drive laser radiation will be needed for obtaining good photoinjector performance.

Choice of the Main Laser

At present this choice is unambiguously determined by the repetition rate/average power, which in turn is decided by the technology of the accelerator.

Normal conducting machines work at low repetition rates, and therefore can afford to use low efficiency robust metallic cathodes, mostly copper. The gun design has been continuously improving, mainly in terms of symmetry and cooling to allow for higher repetition rate (130 Hz for the LCLS design)[1]. From a laser point of view, it is important to note that new designs use a nearly normal incidence geometry, which, on the expense of some quantum efficiency reduction solves the problems related to the tilted pulse front and aberrations associated with the grazing incidence geometry. The design that has recently been implemented for FERMI [2] has the additional advantage of removing the in/vacuum mirror and related problems. However, the main issue of the copper cathode remains the low quantum efficiency (few times 10^{-5} in the 260 nm wavelength range), so to safely obtain the 'magic' 1 nc usually requested by FEL physicists, a pulse energy of about 0.4 mJ has to impinge on the photocathode. Assuming a third harmonic generation conversion efficiency of about 10% and losses associated with the temporal and spatial shaping of up to 70%, we conclude that it would be safe to start with at least 15 mJ pulse energy. The present technology available for reaching reliable operation in this energy range is the combination Ti:Sapphire based regenerative-multipass amplifier system. Importantly, such a system can nowadays be based entirely on diode pumping, which guarantees very high stability, e.g. 2% RMS or better.

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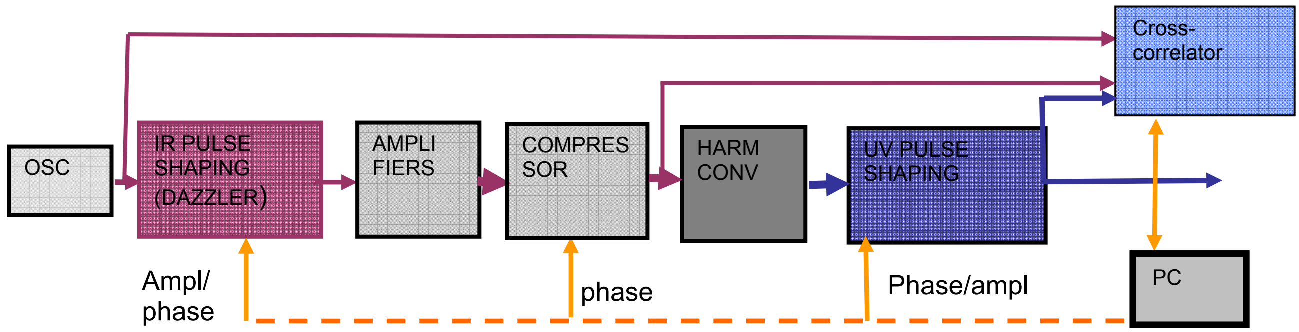

Figure 1: Layout of the pulse shaping system for the FERMI photoinjector laser.

The situation changes for superconducting based machines, where the repetition rates/ average powers can be much higher. Recalling the above mentioned 15 mJ energy per pulse, and assuming a 100 kHz rep rate, an average power of 1.5 kW would be needed, which is not within reach in the near future, even if cryo-cooled amplifiers are used. The solution is to use more efficient cathodes, e.g. Cs_2Te (FLASH, ELBE, European XFEL), GaAs (JLAB, 4GLS), etc. Efficiency of such cathodes can reach 1%. Day-to-day experience at PITZ and FLASH shows that about 1 µJ of pulse energy at 260 nm are needed for the reliable generation of 1 nC. Taking again into account the harmonic conversion efficiency, shaping and conversion losses, an IR energy in the range 20-30 µJ is needed. It should be noted that an additional major requirement in some of the above mentioned machines is the operation in burst mode, where a macropulse containing hundreds of micropulses spaced by hundreds of nanoseconds [3]. There are no commercial systems optimised to operate in such a mode, which lead to the development of a dedicated laser system based on a chain of linear Nd:YLF based amplifiers [4]. This system, initially lamp pumped, has later on been upgraded to diode pumping and showed excellent performance and reliability. Its main limitation comes from the limited bandwidth of the Nd:YLF , so rise and fall time of the flat-top pulse could not be shortened below 4-5 ps [5]. Implementation of new laser media that will be discussed later in this paper should allow to overcome this limitation.

Time Shaping

The photoinjector laser system cannot be discussed without addressing one of its main requisites, namely the capability of pulse shaping. We note that, while in most cases the requested shape is a 10-20 ps long flat-top with less than 1 ps rise/fall times, some new designs require more difficult shapes , like increasing ramp [6], space-time ellipsoid (e.g. 3-D shaping), etc. The pulse shaping for photo-injectors has already been addressed in several publications, see e.g. [7] and refs therein, so here we will only briefly recall the possible approaches and some recent results. In principle, there are two main ultrashort pulse shaping techniques, namely 4-f type Fourier shaping [8] and acousto-optic dispersive modulator (DAZZLER) based [9] shaping. Both of them rely on manipulation of the phase or amplitude relations of the frequency components of the input pulse, which allows to create a new pulse with time structure/shape resolution limited by the inverse bandwidth of the input pulse and the fidelity of the shaping system. A considerable effort has been made to adapt these, originally developed at low energy in the infrared, techniques, for the high energy UV demand of the photoinjector laser. A block scheme of what we believe is the most flexible setup is presented on Fig.1. As it can bee seen , the pulse is shaped both in infrared and UV, with IR shaping used for preliminary optimizing the spectrum and pulse length, while the required final UV temporal shape is obtained in a 4-f type setup based on high efficiency transmission gratings and deformable mirror [10] placed after the harmonic conversion. The phase modulation in UV is based on a linear deformable mirror incorporating 20 piezo actuators, while the amplitude one is done by knife-edge filtering of the wings of the spectrum in front of the mirror. On Fig 2 we show crosscorrelation traces of two typical pulses, a flat to and a ramp, the latter being the shape requested for optimum operation of the FERMI project. The use of the deformable mirror will allow to adjust the exact slope of the ramp optimizing directly the photoinjector and even the FEL performance.

There is a time-domain alternative to the above mentioned frequency domain techniques which could be competitive if a flat-top only shape is required. In this scheme, the final pulse shape is synthesized by using a number of time delayed replicas of a short Gaussian input pulse. The interference of neighbouring overlapping pulses, which would cause modulation, is prevented by alternating S- and P-polarisation for the consecutive pulses. The application of this technique to photoinjector lasers was initially based on a scheme involving cascaded polarisation splitting and recombining arms [11]. An improved version, proposed lately by the same group [12], utilises a common path scheme where the two groups of orthogonally polarised pulses are created using a sequence of birefringent crystal plates (α-BBO) with properly chosen increasing thickness. In this case, the additional phase correction needed for compensating dispersion effects in the plates has been provided by a DAZZLER.

Transverse Shaping

The requested UV beam shape on the photocathode is generally a flat-top with less than 10% RMS flatness and as steep as possible edges. The conversion of the nearly-Gaussian laser beam from the amplifier to a super-gaussian is usually performed in UV by the use of beam shapers based on redistribution of the energy from the centre to the periphery. One of the commercially available solutions (Newport) is based on the aspheric design proposed in [13], while the other one (Moltech) utilizes a combination of lenses with strong spherical aberration. To decrease the sensitivity of the aspheric design, the MBI group developed their own version with lens shapes optimised for generating lower order super-gauss [14]. A very simple approach which is used by some groups (SLAC, SPARC, PITZ) is to aperture and further image onto the photocathode the central part of the image, with the drawback that at least 50% loss is added. In all these cases strong modulations of the input beam, as well as inhomogeneities of the cathode cannot be compensated. The best solution would be the use of a telescope and round deformable mirror, as proposed in [15], incorporated in a genetic algorithm based optimization loop.

It is worth noting that the use of holographic or fiber based homogenizers, which is well developed for other applications, is not possible for the standard gun designs used at present due to long distance between laser insertion port and the cathode. In the future, if back illuminated cathodes research gives good results, the homogenizers may appear to be the best option, of course after optimization to avoid temporal smearing.

SEED LASER

Use of seeding has been proposed in order to improve the longitudinal coherence and shot-to shot reproducibility of FEL pulses. At present the only FEL under construction which is entirely based on seeding is FERMI. For this reason the discussion below will be based mostly on the requirements for the FERMI seed, taking into account also the needs and plans of other groups presented during the recent workshop dedicated to FEL seeding in Frascati [16].

UV Seed

In the case of FERMI the photon production will be based on the principle of the high gain, harmonic generation FEL amplifier that uses multiple undulators and the frequency up-shifting of an initial seed signal in a single-pass [17]. Table 1 summarizes the main requirements for the seed laser, where also the values that have been measured on the system under preparation are presented in the third column. The requested very large tuning range in the UV automatically determines the choice of parametric amplification with consecutive parametric amplification as the only feasible present solution. A 780 nm pumped travelling wave parametric amplification scheme was chosen, see Fig.2, (instead of a 400 nm pumped non-collinear parametric amplifier) because of the availability of high energy commercial system meeting all specs. A general optical layout is shown on Fig.2. An additional upgrade done at Elettra (Mixer 3 on Fig.2) has allowed to shift the UV border towards shorter wavelengths (<200 nm) which is favorable for the FEL operation (see the tuning curve presented on Fig.3). Further shift of this border (down to 170 nm) will be attempted by adding an additional amplifier and mixer stages (dashed line on the figure) and by the use of a KBBF crystal. It is important to note here that one of the major concerns, namely the ability to reach the requested 10^{-4} wavelength stability requirement, has been successfully met.

An extremely important point for the seed laser is also to provide the laser pulses with as small as possible jitter with respect to external trigger (and therefore to the electron bunch). For this reason, the system can be seeded by a frequency doubled Er-doped fibre laser which has intrinsically lower phase noise (and therefore timing jitter when locked) with respect to the Ti:Sapphire oscillators. The use of the Er-doped laser to seed the Ti:Sapphire amplifier , however, required the development of a high efficiency frequency doubling system with broad bandwidth based on chirped periodically poled crystal. At present it can only deliver bandwidths of up to 20 nm which is expected to be further increased by replacing the present (commercial) fibre laser by a home made optimized fibre laser-amplifier combination.

VUV Seed

Clearly, it will be advantageous to provide a seed light at shorter (VUV or soft-X ray) wavelength and decrease the jump in harmonics. The most promising technology for such a seed is recognized to be the high harmonic generation in gases (HHG) which has recently been demonstrated to allow to generate photons even in the

Table 1: Seed laser specifications

Parameter	Specs	Measured
Tunability range (nm)	240-360	195-350
Peak power (MW)	100	>100 (240-360 nm)
Pulse duration (fs)	100	<130 (240-360 nm)
Pulse Energy Stability RMS 5000 shots	<4%	<2%
Timing jitter (fs RMS)	<100 fs (goal 50 fs)	<100 fs
Pointing stab. (**µrad**)	<20 (goal 10)	<20
Wavelength stab.	10-4	<10-4
Beam quality (M2)	<1.5	<2

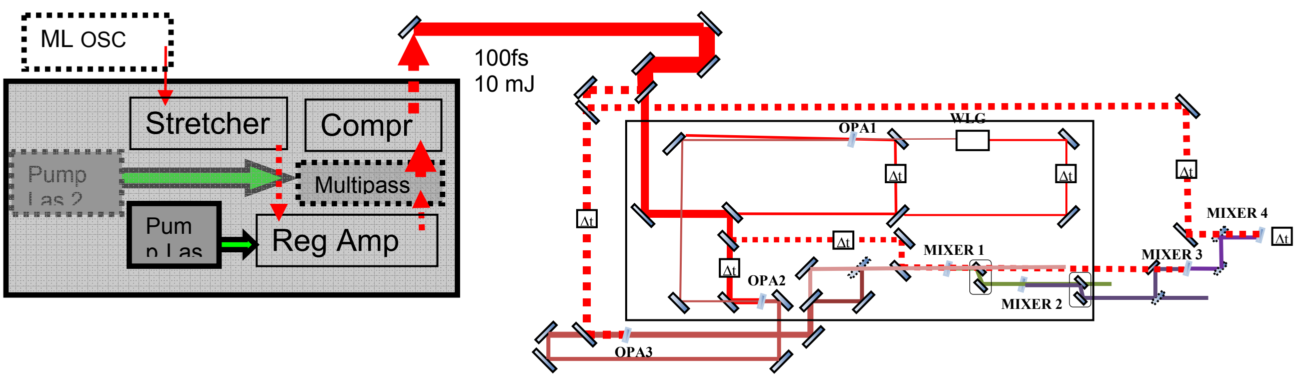

Figure 2: Optical Layout of the FERMI seed laser, upgrades in dashed line.

demonstrated to allow to generate photons even in the

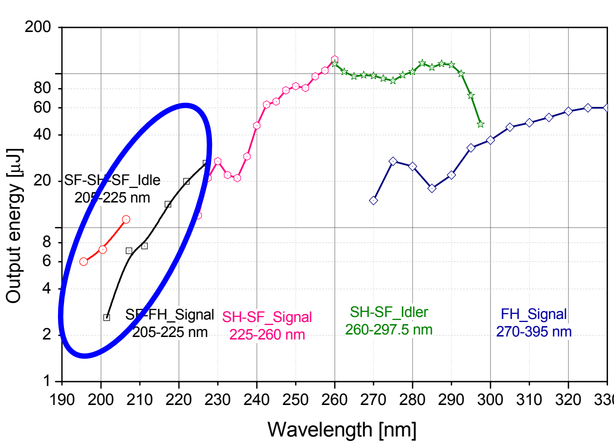

Figure 3: Present tuning curve of the FERMI seed laser.

water window. In terms of peak power, HHG seed based on sub-30 fs ,15 mJ range, Ti:Sapphire pump pump seem to reach even now the goal in the 40 nm range. The main open question remains the tunability of the pump needed to cover the range between two harmonics. A promising way of Ti:Sapphire amplifier tuning using a combination of Dazzler and Mazzler has been recently demonstrated by Amplitude Technology [18]. Our simulations indicated that in combination with bi-color pump this system should be capable of providing sufficient continuous tuning and peak power of the seed. [19]

PROMISING LASER MEDIA UNDER DEVELOPMENT

For the normal conducting machines, i.e. rep rates of up to few hundred Hz, Ti:Sapphire based technology is very likely to remain dominant. It has the potential of much shorter pulses, required e.g. in some new schemes for ellipsoidal bunch production, as well as in the seed laser if HHG in gas is used. In addition, it is a mature technology with commercially available units. Recent improvements in pump lasers (commercially available 100 W range Q-switched pump lasers), in the crystal cooling technology, as well as the amplifier design (downchirping [20]) may allow in the near future to reach and exceed the 50 W level.

Anyway, the better choice for superconducting machines requiring very high average power may still be other laser media which are intrinsically much more efficient (emitting at 1.03-1.05µm while pumped in the 0.97 µm range). In particular, some Yb-doped materials are very good candidates. An Yb:KGW/YB:YAG regenerative plus multistage amplifier system developed at MBI has achieved energy of 150 mJ in burst mode with 800 micropulses per burst. Very promising results both in long cavity mode-locked oscillator regime and regenerative amplifier regime have been reported for Yb:KYW [21]and Yb:Lu_2O_3 [22]thin disk systems: pulse energies approach 10 µJ at MHz repetition rates. These systems are still not mature enough and generally not commercially available, the first Yb:YAG based compact regenerative amplifiers have been commercialised only a few years ago.

In our opinion Yb-doped fibre lasers and amplifiers may have even better chance to become important for high repetition rate FEL applications. The fast advances of microstructured-fibre technology, in parallel with new ideas on fibre amplifier design has allowed to reach impressive average powers (e.g. 135 W) and pulse energies of 100 µJ [23] with pulse durations of few hundred fs.

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