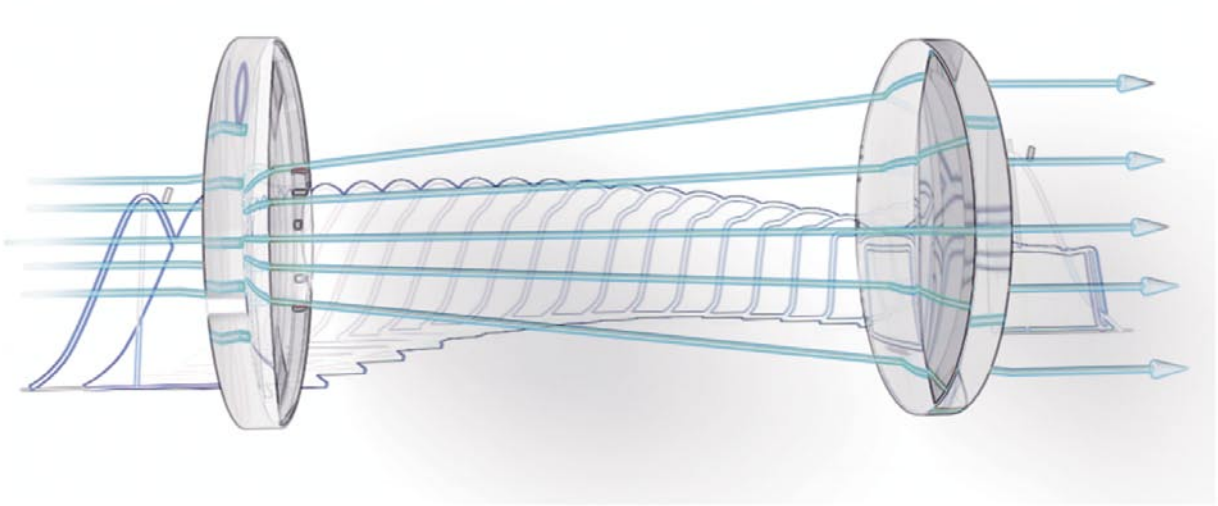

10 Laser Systems

Synopsis

Laser systems will undoubtedly be crucial to determining the overall performance of FERMI. As can be seen from the previous chapters, the laser systems will include the photoinjector laser (PIL), laser heater (LH), seed laser (SL) and beam-line lasers (BLL). In addition, the timing and synchronization system will contain a mode-locked optical master oscillator (OMO). This chapter emphasizes the PIL and SL, as the technology for the other two systems will be very similar; the OMO has already been considered in Chapter 9. The main issues related to the FERMI laser systems have been thoroughly studied during the last year, some of the important points and preliminary data have been summarized and presented in [1]. We note that nearly all the features required of the laser systems by the FERMI FEL design are within reach of readily available laser technology. In contrast, a few characteristics, such as pulse/beam shaping for the photoinjector laser as well as wavelength stability and pulse quality for the seed laser are challenging and will require additional R&D. As it will be shown later, the comparison of the existing laser technologies for obtaining the required parameters indicated the basic unit in all cases to be a Ti: Sapphire chirped pulse amplifier pumped by diode pumped solid state lasers.

The photoinjector laser includes two amplifier stages – a regenerative stage followed by a multipass stage – to reach a pulse energy of 20 mJ in the IR. Pulse shaping is done partially in the IR, by an acousto-optic dispersive filter (DAZZLER), and is completed in UV in a transmission grating-based stretcher or Fourier-system. Beam shaping is done either in the IR or in the UV by an aspheric shaper. A small part (~400 μJ) of the IR beam is split away and transported for use by the laser heater.

The seed laser needs to provide tunable radiation in the UV in two pulse duration regimes: 100 fs and 1 ps. This is flexibility is obtained by using a dual-pulse duration regenerative amplifier. In the 100 fs regime, the regenerative amplifier directly pumps a traveling-wave parametric amplifier (TOPAS) followed by harmonic conversion stages. In the 1 ps regime, output of the output of the regenerative amplifier is further amplified in a two pass stage to ~10 mJ, and then pumps a ~1 ps TOPAS. Beam-line lasers will be based on the same technology, with final pulse energy and wavelength ranges remaining to be specified.

All systems will be synchronized to the timing and synchronization signals by phase-locking loops in the local mode-locked seed lasers. The possibility to use direct seeding by locally amplifying and frequency doubling the fibre distributed 1550 nm sync pulses is under study.

10.1 Photoinjector Laser

The Photoinjector laser (PIL) is a fundamental element in all FEL designs. The pulse and beam quality of this system is crucial to the overall FEL performance, as it is directly imprinted on the emittance 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. In addition, for guns based on copper photocathode, ~0.5 mJ pulse energy in the UV is required, which implies at least one multipass amplifier, followed by two harmonic generation stages.

The rationale for the gun laser specifications presented in Table 10.1.1 were discussed in Chapter 5. Most importantly, the reliable generation of ~ 1 nC of charge with low thermal emittance (i.e. wavelength range 260-270 nm) requires UV pulses with energy~0.5 mJ. Assuming a third harmonic generation conversion efficiency of 10 % and losses associated with the temporal and spatial shaping of up to 70 %, we conclude that one needs to start with >18 mJ per pulse. The present technology available for reaching reliable operation in this energy range is a combination regenerative-multipass amplifier system.

Table 10.1.1: Summary of the required PIL parameters.

Repetition rate	10-50 Hz
Pulse duration	3-10 ps (FWHM)
Pulse shape	flat-top or increasing ramp
Rise-time	0.5-1 ps (10-90%)
Spatial profile	top-hat, ~ 1 mm (up to 2 mm) $1/e^2$ radius
Fundamental wavelength	780-800 nm
UV wavelength (third harmonic)	260-267 nm
UV Pulse energy on the photocathode	~0.4 mJ
Timing stability with respect to RF	< 0.2 ps rms (0.3 ps rms producer spec)
Energy stability in UV	< 3% rms
Stability of the beam position on the photocathode	< 1.5% rms

In addition, the relatively large bandwidth required for pulse shaping leads to the need of initial pulse duration in the 100-150 fs range. The only mature, commercially available lasers that deliver pulses of such energy and duration are Ti: Sapphire-based systems. Relatively new solid state media with direct diode pumping, such as Yb:KYW are very attractive in some respects and are to be considered for future projects; however, at present they do not reach some of the essential parameters required (i.e. pulse energy). Consequently we have selected Ti:Sapphire as the active medium for the FERMI photoinjector laser.

10.1.1 Laser System Layout

A block diagram of the Ti:Sapphire based femtosecond amplifier system is shown on Figure 10.1.1. It consists of a mode-locked femtosecond oscillator, a regenerative amplifier and a multipass amplifier stage.

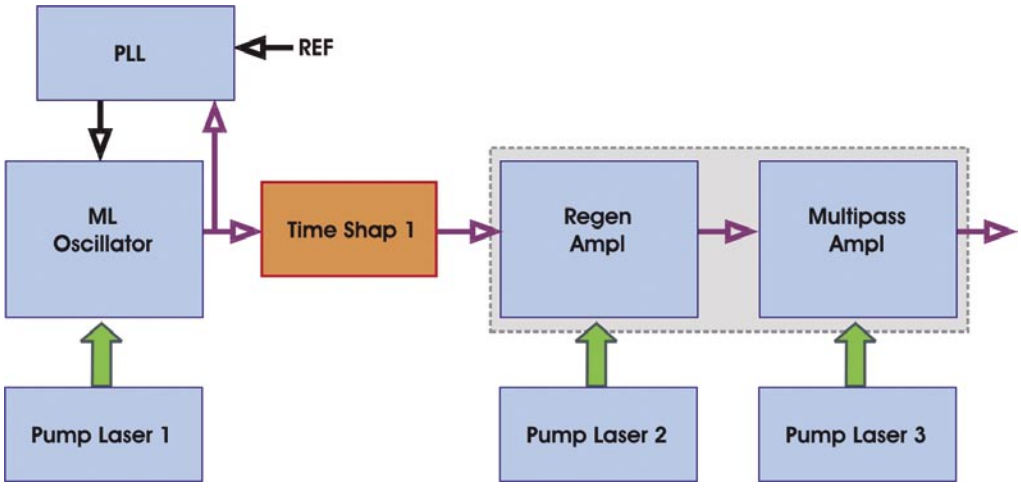

Figure 10.1.1:
Laser system configuration.

10.1.1.1 Mode-Locked Oscillator

The mode-locked oscillator generates the seed pulses for the system; hence its quality is crucial for the overall system performance. The first version of the FERMI system is based on a Kerr-lens mode-locked Ti:Sapphire laser, however a fibre laser based solution will also be tested.

The principal characteristics of this system are as follows:

Pulse duration/bandwidth: to account for 1) the requirements of temporal shaping, 2) bandwidth limitations coming from group-velocity mismatch effects, and 3) the problems in manufacturing very thin large cross-section BBO crystals, we have chosen the oscillator bandwidth in the range 12-15 nm.

Central wavelength: 770-780 nm represents a good compromise between the gain of the active medium and the photocathode efficiency corresponding to the third harmonic.

Repetition rate: 78.893 MHz.

Phase locking loop: this critical sub-system determines the fidelity of locking to an external reference signal. Details on the techniques used and expected performance were already given in Chapter 9. The initial photoinjector laser configuration is based the Synchro-lock PLL™ of Coherent, which was specified to guarantee better than 300 fs rms jitter in the 10 Hz-10 MHz range.

10.1.1.2 Amplifiers

The laser oscillator pulse energy is typically in the few nJ range and has to be boosted to ~20 mJ by the amplifier chain. A proven approach is to use a regenerative amplifier (1-2 mJ) followed by a multipass stage. Schemes that rely on an entirely multipass design while possible, often suffer from problems with beam quality and alignment sensitivity. Indeed, most commercial products are now based on regenerative amplifier technology for energies up to 2-3 mJ and employ one or more multipass stages when higher energies are needed. In all cases, chirped pulse amplification scheme is used [2].

The main decision concerning the FERMI photoinjector laser was the choice of pumping technology. In fact, the required repetition rate and energy level place the photoinjector laser system on the border between flash lamp and diode pumping. Lamp-pumped Nd:YAG/YLF, frequency doubled lasers are best suited for 10 Hz operation. At 50 Hz they become less stable and display lower beam quality. Moreover, for a system with 24 h/day operation, flash lamps would need to be changed every 5-6 days assuming lifetime of 3.10^7 shots. In contrast, diode pumping is much more expensive and may involve higher running costs. To reach the 20 mJ, energy range requires several pump lasers if CW pumping is used. Alternatively, using a quasi-CW-pumped, diode-based system in general reduces diode lifetime and raises operating costs. Balancing all these considerations and giving highest priority to laser system stability, repeatability and beam quality, we chose the CW diode-based pumping scheme shown in Figure 10.1.2. The pump beams in the green come from one Evolution 15™ and two Evolution HE™ lasers, delivering 10 mJ and 2x40 mJ, respectively.

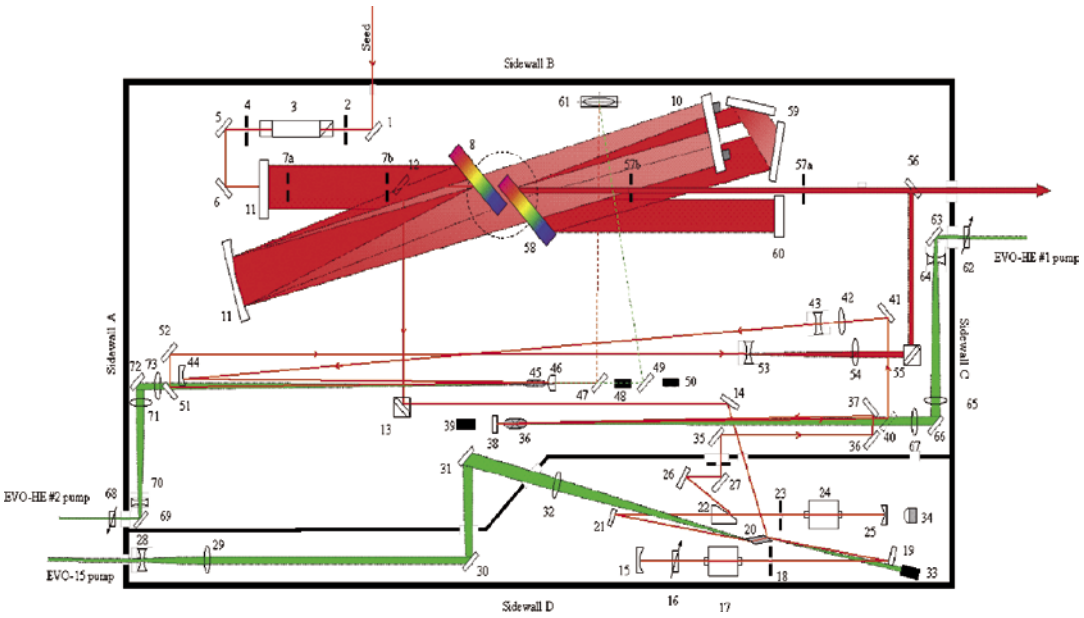

Figure 10.1.2:
Optical scheme of the amplifiers.

10.1.2 Pulse Shaping

The laser system described above can deliver pulses of different duration and shape, determined by the bandwidth of the seed laser and the alignment of the amplifiers, compressor, etc. Generally, the master laser oscillator delivers nearly transform limited, $sech^2$ – type pulses, which can be fitted by a Gaussian function as well. Due to uncompensated, high order dispersion in the amplifier, the 100 fs system would typically produce near Gaussian pulses with a time-bandwidth product 1.2-1.4 times the transform limit. The pulse shaping converts this pulse into one with rise- and fall times of 0.5-1 ps and duration in the 5-10 ps range. The shape requested at present is an increasing ramp; however the system design would also allow the generation of more complex shapes, as well as a flat-top according to the original specifications. Detailed considerations about the different solutions and schemes that were studied are given in [1]. Here we will only briefly recall that there are two main approaches. The first one, furthermore referred to as Fourier-shaping , is based on a spatial displacement of the spectral components of the incoming pulse, modulation of their amplitude and/or phase distribution and then recollimation of these components into a modulated light pulse [3]. The basic optical setup implementing this idea is a dispersive 4-f system consisting of two gratings and a unit magnification telescope [3,4]. The spectral modulation is performed by a spatial light modulator positioned in the common focal plane of the lenses.

The second technique is based on a device called DAZZLER [5]. It also works in the frequency domain, however without spatial separation of the pulse frequency components. The laser pulse is sent trough an acousto-optic modulator where a properly shaped acoustic wave is present. The pulse spectral components are diffracted only by acoustic wave regions that match their wavelength and therefore can be manipulated both in amplitude and phase by the amplitude and positions of these regions [6].

Analyzing the advantages and limitations of the two above mentioned techniques, it can be seen that a hybrid two-stage pulse shaping incorporating the two main shaping techniques is needed in order to satisfy the PIL shaping requirements [1,4] The foreseen system layout is shown schematically on Figure 10.1.3. Initial shaping of the seed 100 fs pulse from the laser oscillator is provided by an acousto-optic dispersive filter (DAZZLER) [2,3] upstream of the regenerative amplifier. The DAZZLER is programmed for both amplitude and phase modulation, where the first shapes the spectral amplitude to the desired shape, and the latter inserts the desired phase delay function.

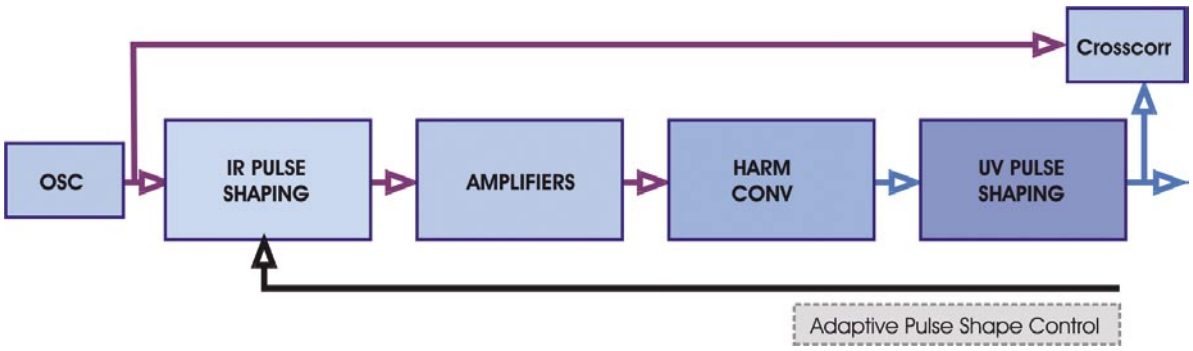

Figure 10.1.3:
Pulse shaping sequence.

The phase modulation at this stage is not yet sufficient to produce the final pulse. We adjust the pulse duration at the amplifier exit (mainly by adding a second order phase term by the grating compressor) to yield a best compromise between a) high conversion efficiency and b) minimum pulse distortion due to high order nonlinear effects (e.g. self-phase modulation). After the harmonic conversion, we then use a UV shaping unit to obtain the final pulse duration and shape.

Two alternative configurations are under still investigation. The simpler one is a two pass grating stretcher that permits expanding the pulse to the desired length by adding second-order dispersion. If a more complex phase function is needed, we will implement 4-f type Fourier shaping, based on a deformable-mirror modulator. In both cases the setup will employ high-efficiency, transmission diffraction gratings, now being tested at ELETTRA.

In order to illustrate better the described scheme, on Figure 10.1.4 we present the results of a simplified simulation of pulse shaping which generates the increasing ramp requested for the FERMI 'long bunch case'. The simulation is done starting with a transform-limited Gaussian pulse at 800 nm having 12 nm of FWHM bandwidth (dashed blue line on the left graph). The spectrum shown in red line is obtained after amplitude modulation by the Dazzler. In addition, it is assumed that the latter completely compensates the residual high-order dispersion of the system. The pulse shape shown by red line on the right graph corresponds to the amplifier output, where a second order dispersion of about 60000 fs^2 has been introduced by detuning the compressor. Assuming that the third harmonic generation is performed in sufficiently thin BBO crystals, so GVM and spectral acceptance effects can be neglected, the UV pulse shape (dashed blue line) is proportional to the third power of the IR one. The final shape and duration, shown by solid blue line are obtained by adding only second order dispersion from the UV grating stretcher. We note that this stretcher will inevitably add also a third order dispersion term on the order of 100 000 fs^3 , which is in principle possible to compensate in advance by the Dazzler, so it has not been taken into account into the above presented simulation. As mentioned above, in case the DAZZLER compensation is not sufficient the odd dispersion terms will be cancelled by the use of deformable mirror.

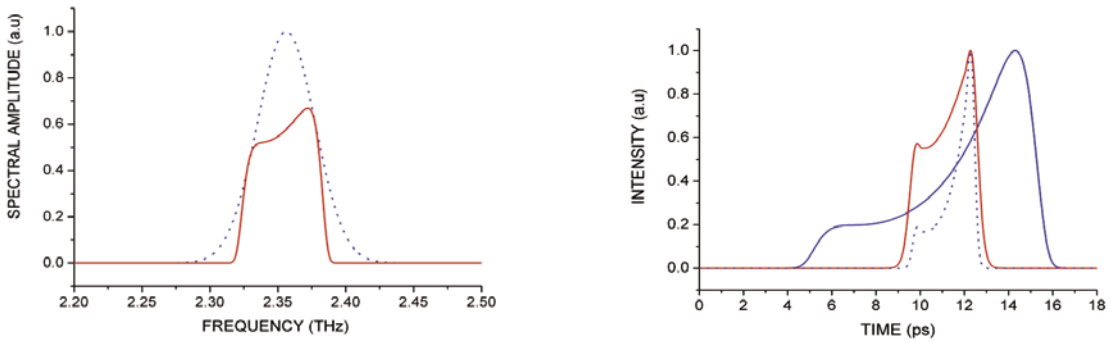

Figure 10.1.4:
Pulse shaping simulation. Left: Input optical spectrum (dashed blue) and amplitude modulated DAZZLER output (red solid); Right: IR pulse shape after amplifier (red), initial UV pulse (dashed blue), stretched UV pulse (solid blue).

10.1.3 Beam Shaping

The ideal spatial (transverse) beam distribution is close to flat-top. Therefore, we need an optical system that transforms the original (nearly Gaussian) shape of the laser beam into a uniform profile.

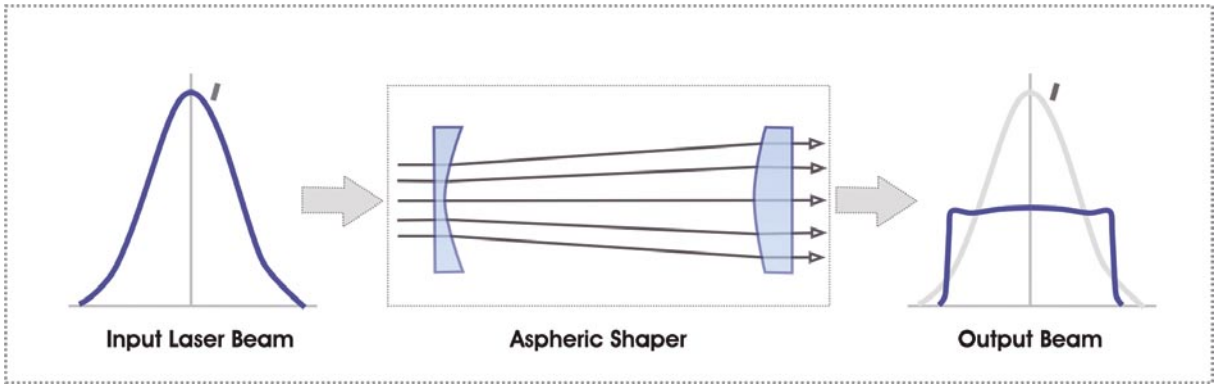

Figure 10.1.5:
Sketch of beam shaping.

Laser technologists have attacked this challenge for many years and have proposed numerous approaches (see [4,5] and Refs therein). Our preliminary analyses and our experiments at ELETTRA (and also at LCLS, see [6]) indicated that aspheric shapers [5] with the modification using a Galilean telescope (See Figure 10.1.5), can meet the specifications for the photoinjector laser system. The main advantages are low insertion loss, high damage threshold and the possibility to work directly in UV. Such shapers are commercially available from two suppliers. Figure 10.1.6 presents an experimental result obtained at ELETTRA using MolTech aspheric shaper in the infrared. Similar profiles have been obtained in the UV by using the Newport version of the shaper [6].

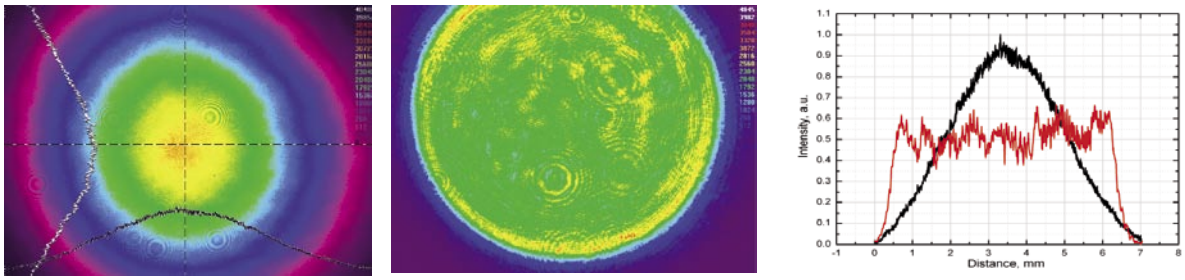

Figure 10.1.6:
Experimental results using a MolTech pi- shaper: images of input Gaussian (left) and output flat-top (center) beams; cross-section of both beams (right).

The figure shows that, while on average the shape is close to flat-top, the ripple is higher then 10%. Most of the ripple likely originates from imperfections in the aspheric lenses. Additional beam deterioration may come from the non-perfectly Gaussian shape and asymmetry of the laser beam after amplification and harmonic conversion. We plan further R&D to improve the performance of the beam shaper.

10.1.4 Harmonic Generation

Figure 10.1.7 displays the main features of the setup implemented for third harmonic generation (THG). The principal features of the design are as follows:

Short, type I BBO crystals for both stages. Our analysis, done using in-house codes plus the freeware SNLO [7] shows that this combination yields the best combination of efficiency and accepted bandwidth.

The "time-plate" design used is more compact and robust than the more common interferometer-like designs, in which the fundamental and SH light are separated after the SHG crystal and recollimated after the polarization rotation.

Beam-size and pulse duration will be adjusted in order to work at peak power level yet avoiding high order non-linear effects in order to keep pulse phase clean.

~15% efficiency has been demonstrated with IR pulses in the 1 mJ range.

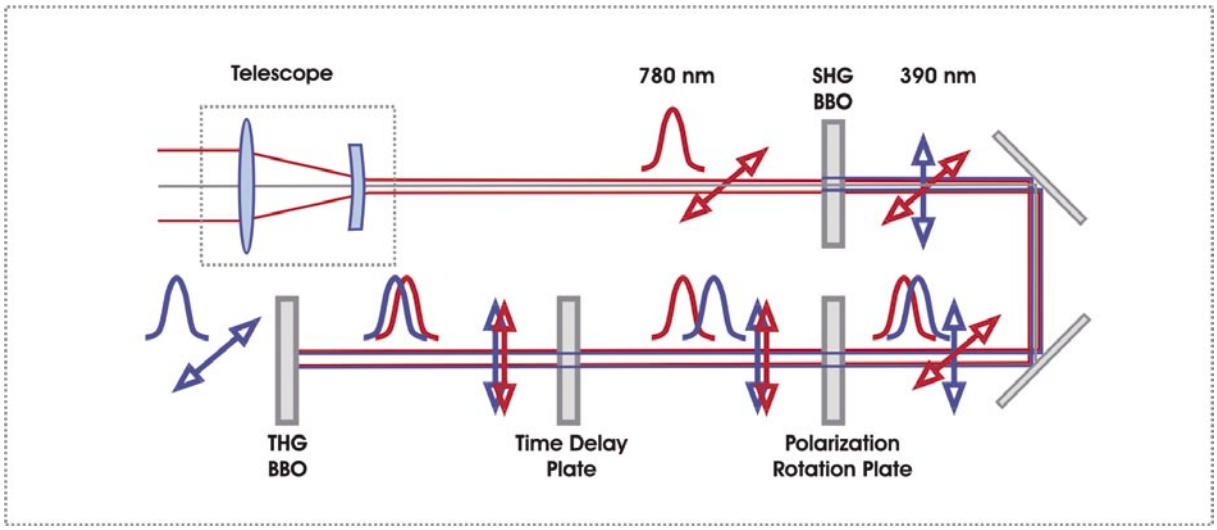

Figure 10.1.7:
Harmonic generation setup.

10.1.5 Beam Transport and Imaging

The beam transport system must propagate the beam from the PIL laser room to the photocathode without distorting its spatial and temporal shape; it also must provide zooming capability. We will optimize the complete engineering design of the optical system using ray tracing software. The main features of the PIL beam transport system (see Figure 10.1.8) are as follows:

Flat-top beams with steep edges tend to develop sharp diffraction peaks and rings upon propagation; therefore, the optical system is based on consecutive imaging with the photocathode plane coinciding with the end image plane of the relay imaging.

The required zoom can be obtained using a commercial motorized UV zoom lens.

The longest propagation distance is the straight section between the laser room and photoinjector in which the beam propagates in a low vacuum enclosure.

Nearly normal incidence geometry is chosen for the photocathode, thus eliminating the need for elements for pulse /beam tilt compensation.

Beam position is monitored on several position sensitive detectors (or CCDs) and controlled by steering mirrors.

Pulse arrival time on the photocathode can be adjusted by variable optical delay line.

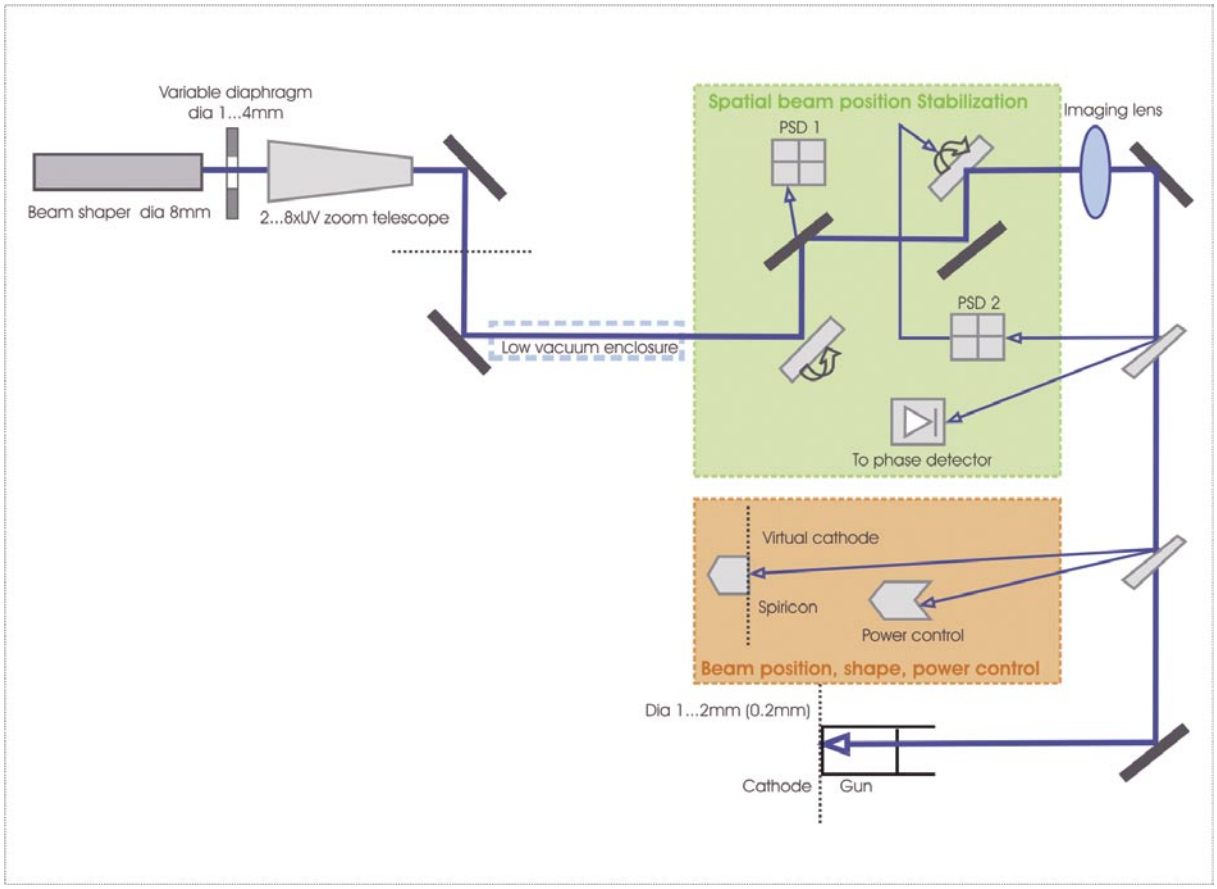

Figure 10.1.8:
Optical beam transport system of the PIL.

10.2 Seed Laser System

10.2.1 Main Requirements

The main requirement for the this laser source is to deliver sufficiently high peak power (~100 MW) in the UV, at wavelengths tunable in a rather large range 240-360 nm and in two pulse durations regimes, namely 100 fs and 1 ps. Obviously, maximum obtainable stability of all parameters is also requested, in particular central wavelength stability and low jitter. The main parameters are summarized in the table below.

Table 10.2.1: Seed Laser parameters.

Parameter	*Specification*	*Note*
Pulse duration	100 fs; 1 ps	Switchable, not real time
Wavelength range, nm	240-360	Real time tuning in sub-ranges
Jitter, rms	< 100 fs	
Wavelength stability	< 0.1%	
Energy stability, rms	< 5%	
Pulse/beam shape	Gaussian	Low residual phase modulation
Spot-size at input, μm	200-300	

10.2.2 Seed Laser Configuration

At present the requirement of such a broad tuning in the UV can only be met by using optical parametric amplification (OPA) in the visible or near infrared followed by consecutive harmonic generation. Moreover, the high UV pulse energy needed (~100 μJ with 1 ps long pulses) requires pumping the parametric amplifier with IR pulses of 10-15 mJ. These considerations lead to our design of a system configured as shown in Figure 10.2.1.

A single Ti:Sapphire based pump source for both the short and long pulse regimes provides a pulse energy of 2.5 mJ and 10 mJ, respectively. Two options remain under consideration for the short pulse regime. In the first one (a on Figure 10.2.1) a white-light, continuum based, non-collinear OPA (NOPA) pumped by the SH of the Ti: Sapphire at 390 nm, is used [8]. This scheme has the advantage that a single SHG stage suffices to cover the full UV range needed. Also, it gives some flexibility in varying the duration of the generated pulse, because the NOPA process can yield substantial shortening of the pump pulses. However, this scheme has some points that need further study:

No commercial product provides the required energy per pulse in the UV; the available literature describes systems that are about a factor of 2 to 5 lower in energy. Scaling the pump energy by parallel scaling of spot size in the NL crystals should allow us to reach the required values.

Wavelength stability is of crucial importance for the FEL seed laser. At present there is no experimental data on NOPA performance in this respect. We expect that by adding an accurate system for wavelength control of the white-light-seeded stage, the NOPA output wavelength stability will be limited by the pump laser one.

The second option is the use of a traveling wave OPA scheme (TOPAS), schematically shown in the lower box (**b**) of the figure. In this case the pump is directly at 780 nm, and tunable IR signal and idler wavelengths are produced. These signals are subsequently frequency doubled and mixed in different stages to produce tunable UV radiation in three slightly overlapping ranges that allow us to cover the full required range.

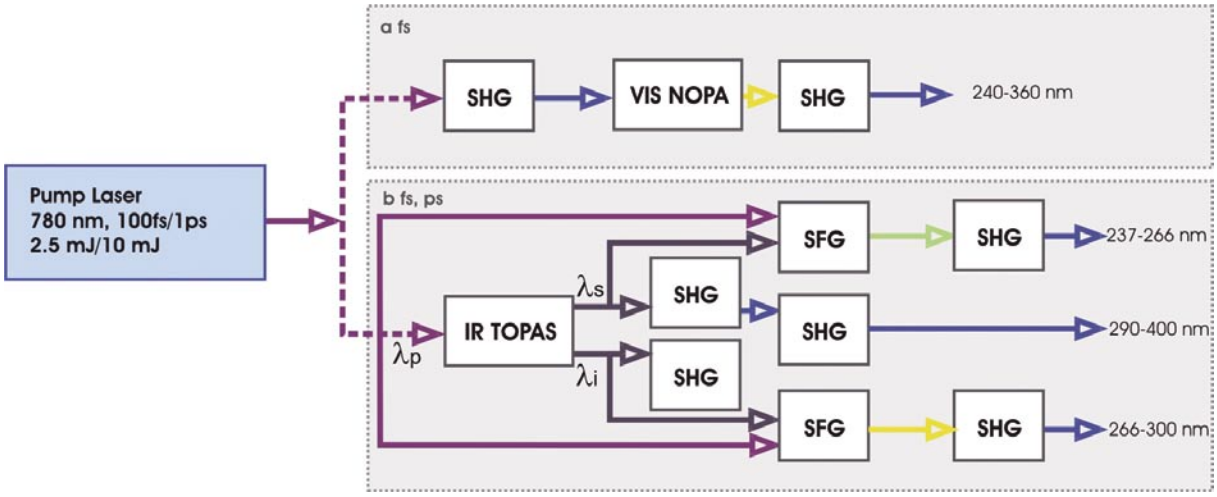

Figure 10.2.1:
Possible Seed Laser configurations: a. NOPA based scheme (fs regime only) b. TOPAS based schemes, both fs and ps version available.

While this scheme is more complicated than the NOPA, its advantage is the availability of a commercial version produced by Light Conversion (www.lightconversion.com). This company can built both 100 fs and 1 ps models with specifications similar to the ones presented in Table 10.2.1. An example of a tuning curve measured on an installed fs system is shown below.

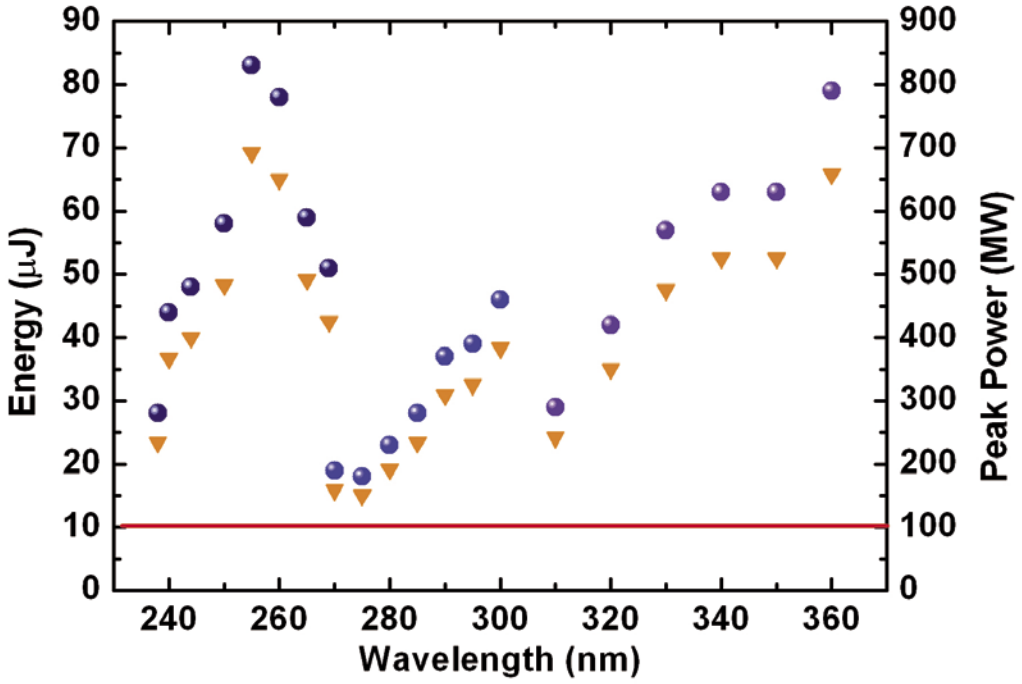

Figure 10.2.2:
Tuning curve of a fs TOPAS by Light Conversion. Circles: measured data in 3 mJ pumped system; triangles: data scaled to 2.5 mJ pump energy.

At all wavelengths of interest this commercial system provides well above the requirement of 100 MW peak power even with 2.5 mJ pump energy. Consequently, only a regenerative amplifier is needed in this case. In 1 ps operation the required minimum pulse energy is 10 times higher, i.e. 100 μJ. Fortunately, the conversion efficiency both in the TOPAS and in the nonlinear mixing stages will also be higher due to strongly reduced group velocity mismatch (GVM) effects. We estimate that ~ 10 mJ of pump energy at 780 nm should be sufficient for reaching ~100 μJ per pulse. The system layout is therefore correspondingly determined: a single pump system contains both the 100 fs and 1 ps sub-systems (see Figure 10.2.3). In short pulse option, the pulse is extracted after the regenerative amplifier and, after compression, pumps a fs-TOPAS. Alternatively, the same seed pulse can be fed into the long pulse optical chain, where it enters a ps stretcher with spectral filtering to reduce the bandwidth; it then passes through the same regenerative amplifier followed by an additional two-pass amplifier.

The pump laser system is now available at ELETTRA. We plan a series of experiments to measure and improve both wavelength stability and beam quality in the near future. In addition to the required dual pulse duration, an important difference with respect to the photoinjector laser is the more stringent jitter requirement (<100 fs rms). A possible way to tackle this need is to replace the Ti:Sapphire seed oscillator with a frequency doubled fibre laser which has intrinsically smaller phase noise. In addition to jitter reduction, the use of fibre laser opens up the possibility to consider the 'direct seeding' approach

(see Chapter 9) which offers additional advantages in terms of system reliability, integration, etc. We have recently started experimental studies on the optimization of the frequency doubling efficiency of a femtosecond fibre oscillator, which is one of the key points which will determine the applicability of the above mentioned approach.

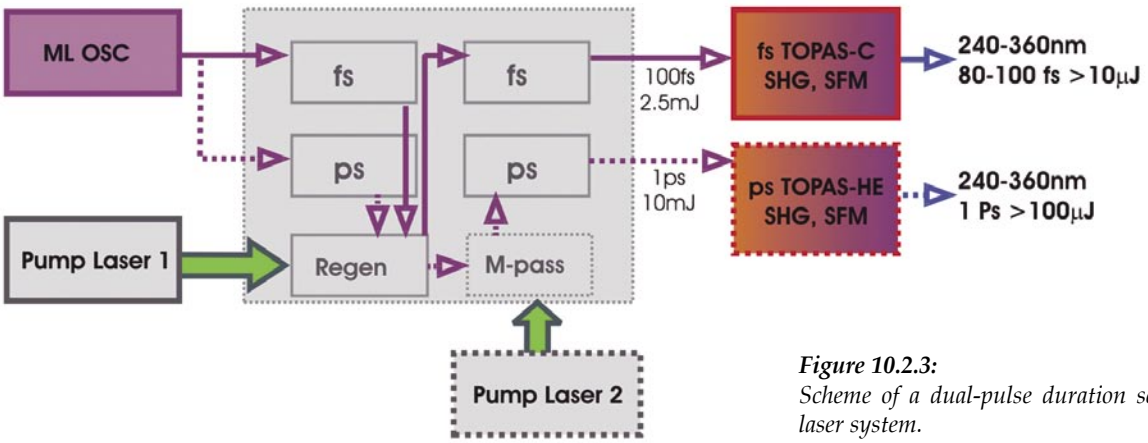

Figure 10.2.3:
Scheme of a dual-pulse duration seed laser system.

10.3 Other Laser Systems

10.3.1 Laser Heater

The functional requirements of the laser heater were introduced in Chapter 6. This laser heater is positioned at about 8 m from the photoinjector. There is some freedom in choosing its exact wavelength; however with respect to diagnostics, a near infrared wavelength is better. Pulse duration and peak power should be in the 15 ps and 10 MW ranges, respectively; the bandwidth of the pulse can be ~10 nm or more. A straightforward means of meeting these requirements is to use a small part of the IR (780 nm) output of the photoinjector laser (PIL) by inserting a 2-4 % beam sampler after the compressor of the PIL. The pulse will then be stretched to about 15 ps by a compact grating stretcher placed on the PIL laser table, and then transported to laser heater position. The requisite optical beam transport and imaging system is very similar to that used for the gun. The available pulse energy provides sufficient margin for spatial and temporal expansion of the beam in order to guarantee good overlap with the bunch at the heater.

10.3.2 Beam-Line Lasers

As already outlined in Chapter 4, a large fraction of the experiments on FERMI will be of 'pump-probe' variety. Therefore, all experimental beam-lines will be eventually equipped with an ultrafast

laser system. Detailed description of the requirements for these systems goes beyond the scope of this CDR. However, for the sake of completeness, a few general observations are useful. A typical source for pump-probe measurements at FERMI would have the following features:

- Lockable with high accuracy to the timing and synchronization signals of the machine, ideally the jitter should be a few times smaller than the pulse duration
- Pulse duration/bandwidth that corresponds to the FEL pulse duration. Ideally, each system should support both short pulse (<100 fs) and long pulse (narrow bandwidth) operation with >1 ps pulse length
- Pulse energy in the few μJ range
- Wavelength – tuneable in bands from UV (>200nm) to IR (2-10 μm).

The ideal beam-line laser is thus very similar to the seed laser described in Ch.10.2. The optimum technology of building it is a fixed-wavelength, amplified, ultrafast laser followed by an OPA with properly chosen harmonic generation and mixing stages. To meet the stringent jitter requirements, this system also must contain a phase-locking loop scheme to allow sub-100 fs jitter values.

10.4 References

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