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Major technical requirements

Advanced kilojoule nanosecond laser for generating 10 PW beamline operating at augmented shot rate

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Background

ELI-Beamlines will be a high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. It will be an international user facility for both academic and applied research, slated to provide user capability from late 2017. The main objective of the ELI-Beamlines project is delivery of ultra-short high-energy laser pulses for the generation of secondary sources of electromagnetic radiation (e.g. high brightness X-ray sources) and for the acceleration of charged particles (electrons, protons or low-Z ions), and to programmatically employ those in a wide area of both fundamental and applied research. Covering a wide range of applications requires installation of several laser systems each having a different set of output parameters. The ELI-Beamlines will thus utilize several state-of-the-art laser technologies as identified in the ELI White Book to cover the required range of parameters.

The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy laser pulses for the generation and applications of high brightness X-ray sources, for particle acceleration, and for research projects in high-field physics and laboratory astrophysics. One of the key components of the ELI-Beamlines facility for the fundamental research is the beamline L4, which is projected to generate pulses with 10 PW peak power.

The laser system sought shall address the major user requirements for a system that will allow achieving the following major elements of the ELI-Beamlines mission:

- Laser electron and proton / ion acceleration using PW and 10 PW high energy pulses
- Plasma physics and laboratory astrophysics using ns-duration kilojoule laser pulses, alone or in combination with PW pulses
- New coherent X-ray sources
- High-field frontier and fundamental physics
- Extreme intensity field via flying mirror

The generation of highly accelerated 50-100-GeV class electrons and 1-GeV class protons requires high-energy pulses with peak power of 10 PW and beyond, with duration of typically 100 to 300 fs. Similar parameters are required for the creation of a so called flying mirror with transverse size useful to achieve and stabilize an extreme intensity field. It was identified by top-level user requirements that laser pulses with energy significantly exceeding 1 kJ, delivered in a single aperture, are required. The laser system sought will make possible advanced user projects in the fields of physics of dense plasmas and of laboratory astrophysics. The required technology shall enable implementation of a kilojoule beamline generating 10 PW peak power in ≤150 fs pulses, and later should also allow pumping of large-aperture OPCPA amplifiers. The system shall be designed with the dispersion management system enabling adjustable length of the compressed pulse up to 100 ps. The proposed technical solution is required to be validated in generation of petawatt-class pulses at 100 J or higher energy and the bid must credibly demonstrate their scalability to >kJ pulses and to shot rate of 1 per minute and higher.

1. Scope of the delivery

Required are design, assembling, testing, performance optimization, and delivering to ELI-Beamlines a laser system capable to deliver pulses with energy of at least 1.2 kJ in a single aperture, with duration of the uncompressed pulse of the order of few ns, and with sufficient bandwidth to allow for direct pulse compression compatible with reaching 10 PW peak power (see Section 2.2). The pulses must be amplified in the CPA[1] (chirped pulse amplification) regime, and must be generated from a short-pulse <100 fs oscillator that can be synchronized to an external clock pulse train with fs accuracy.

Additionally the system has to be capable of producing nanosecond pulses with programmable temporal shape, generated and amplified in non-CPA[2] regime.

The technology used should enable achieving shot rate of 1 per minute and beyond. The system should feature closed-loop control of CPA temporal pulse profile and of the beam wavefront profile, and shall include machine safety controls sufficient to ensure routine and robust operation at full energy.

The energetics of the front end of the system must provide a possibility of seeding amplifiers to generate an additional auxiliary beam, capable to provide the identical bandwidth as the main kJ beam in the CPA regime.

2. Laser system description

2.1 Laser System design

The proposed design must include a short-pulse oscillator synchronizable to external clock with fs accuracy, front end and power amplifiers. In order to generate long (nanosecond) pulses in the non-CPA regime, the system should be equipped by separate narrowband oscillator and front end with programmable temporal pulse shaping capability to generate temporally structured nanosecond kilojoule output pulses for advanced laser-plasma experiments.

The proposed solution shall involve pulse compressor capable of direct compression of the kJ pulses to generate 10 PW peak power in 100-150 fs pulses. It is required that the delivery includes diffraction gratings and full set of optical components for the compressor.

Besides the kilojoule main beam the laser shall also deliver an auxiliary output with energy of 120 to 150 J that will be used as probe for laser-plasma experiments; it is acceptable if the auxiliary pulse is produced at the expense of energy of the main kJ pulse. The auxiliary output should have bandwidth allowing compression of the pulses to ≤150 fs and reaching PW peak power. The compression, required only when the main kJ beam is delivered uncompressed, may be achieved by routing the auxiliary beam into the 10 PW compressor or in an independent compressor.

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[1] The CPA regime means the amplified pulse is chirped and its spectral bandwidth is sufficient for compression to ≤150fs.

[2] The non-CPA regime means that the oscillator output is not chirped prior amplification and bandwidth of the amplified pulse is typically < 0.5 nm (FWHM).

The delivered system must include all necessary power supplies and integrated system controls.

The laser system has to be capable of an independent operation. Additionally, the system has to be ready for a fs level synchronization to an external clock (a 240 MHz optical pulse train) and to external electronic triggers generated by ELI electronic timing system necessary for operation of any subsystems (e.g. pulse pickers, power supplies etc.). Possibilities of cooperation of ELI-Beamlines in implementation of the cross-correlator and the electronic timing system generating the external triggers for achieving the fs synchronization are mentioned in the Section 2.4.

2.2 Major performance requirements (design parameters)

The performance requirements of the laser are stated in the table below and represent a **set of values that must be simultaneously met by the proposed design**. The proposed technical solution must be supported either by parameters achieved in a system built formerly by the Bidder or by relevant quantitative figures substantiated by numerical or analytical calculations showing that the designed system is demonstrably capable of reaching the required parameters.

Relevant required values shall be achieved both at the Supplier's facility and upon installation of the system in the ELI-Beamlines premises. The parameters requiring compression of the full aperture beam are to be demonstrated only in the ELI-Beamlines premises upon installation.

<table>
<tr><th colspan="2">Parameter</th><th>Minimum requirement</th><th>Target specification</th></tr>
<tr><td colspan="4">Main beam</td></tr>
<tr><td colspan="2">Energy [1]</td><td>1.2 kJ in a single aperture</td><td>≥1.8 kJ in a single aperture</td></tr>
<tr><td colspan="2">Peak power</td><td>10 PW</td><td>>10 PW</td></tr>
<tr><td colspan="2">Output beam size [2]</td><td colspan="2">max. 40 cm x 40 cm</td></tr>
<tr><td colspan="4">Auxiliary beam [3]</td></tr>
<tr><td colspan="2">Energy</td><td>150 J in a single beam</td><td>≥200 J in a single beam</td></tr>
<tr><td colspan="2">Peak power [4]</td><td>1 PW</td><td>>1 PW</td></tr>
<tr><td colspan="2">Beam size [5]</td><td colspan="2">max. 20 cm x 20 cm</td></tr>
<tr><td colspan="4">Both beams</td></tr>
<tr><td rowspan="2">CPA regime</td><td>Output pulse duration (FWHM) [6]</td><td>≤150 fs</td><td>≤120 fs</td></tr>
<tr><td>Adjustability of compressed pulse [7]</td><td colspan="2">From minimum pulse duration to 100 ps</td></tr>
<tr><td rowspan="4">Non-CPA regime</td><td>Output pulse duration [8]</td><td>0.5 to 5 ns (adjustable)</td><td>0.1 to 10 ns (adjustable)</td></tr>
<tr><td>Programmable temporal pulse shaping</td><td colspan="2">Yes</td></tr>
<tr><td>Time step of pulse shaping</td><td>150 ps</td><td>100 ps</td></tr>
<tr><td>Minimum programmable intensity step within the time profile of the pulse,</td><td>2%</td><td><1%</td></tr>
</table>

	as a percentage of the peak intensity I_2 [9]		
Central wavelength		800-1200 nm	
Shot rate [10]		1 per minute	Several per minute
Contrast (main pulse to pre-pulse/s power) [11]		$1:10^{11}$	$1:10^{13}$
Beam intensity spatial profile modulation (peak-to-peak) [12]		Smaller than +/-15%	Smaller than +/-10%
Shot-to-shot pulse energy RMS stability		<10%	5%
Beam pointing stability [13]		<10 µrad	5 µrad
Output beam quality: encircled energy in diffraction limited spot [14]		60%	>80%
Active beam wavefront correction [15]		>+/- 2 lambda, spatial sampling sufficient for 4th order Zernike correction	>+/- 5 lambda, spatial sampling sufficient for 6th order Zernike correction
Energy in 2nd and 3rd harmonics in the long-pulse (non-CPA) regime [16]		≥800 J	>1 kJ
Dimensional footprint [17]		max. 15 (l) m x 7 (w) m x 3(h) m	
Operation		Independent, externally synchronizable	
Warm-up time		Less than 2 hours	Less than 1 hour

[1] The proposed solution must be designed with aim to generate 10 PW peak power; in the long-pulse regime the laser should provide energy of 1.5 kJ or higher; single aperture means the output laser field is spatially coherent and can be transported within this aperture over a distance of >>10 m

[2] Size of the uncompressed beam measured at 0.1% of the peak intensity. Peak intensity is defined as the mean intensity of the flat top part containing 80% of the total energy. If applicable, the two sides of the rectangular profile may have ratio max. 1.3. The clear aperture of the compressed beam has to fit in a 900 mm vacuum pipe

[3] The auxiliary output may be extracted either from the kilojoule output or from other point in the laser chain

[4] Compression of the auxiliary beam is required when the main beam is delivered uncompressed. The compression may be thus achieved e.g. by routing the auxiliary beam into the 10 PW compressor.

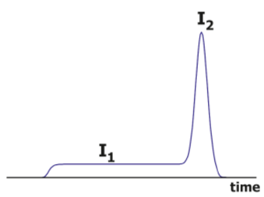
[5] Size measured at 1% of the peak intensity. The two sides of the rectangular profile may have ratio max. 1.3

[6] Minimum requirement is that compressibility at the Supplier's premises is demonstrated using small (≥50 mm) subscale-aperture sampled from several representative locations of the main beam after the final amplifier

[7] With broadband front end; adjustable pulse duration should be generated either by tuning the stretcher and/or the compressor in way to introduce minimum high orders of dispersion as possible.

[8] Requirement given by needs of advanced high-energy "nanosecond" laser plasma experiments; measured at 0.1% of the peak intensity within the pulse

[9] With I_2 being the peak intensity within the pulse, the highest programmable ratio of the lowest intensity (I_1) to I_2 within the pulse is 1:50 with 2% intensity step, and >1:100 with <1% intensity step



[10] Scalable to several shots per minute

[11] Over timescale of 10 ns to 20 ps before the pulse, without using plasma mirror. The proposal has to specify how the contrast will be measured. The proposal has to describe techniques that will be

employed and that are demonstrably capable, with a design margin, to achieve the required contrast value.

[12] With respect to average flattop peak intensity, in the central region containing at least 80% of total energy. The near-field spatial profile must approximate a Gaussian of the 8^{th} or higher order.

[13] FWHM value over 60 consecutive shots (corresponding to 1 hour operation at shot rate of 1 per minute).

[14] Measured using low-energy split off from the output beam: fraction of total output energy encircled within a diameter defined as 1.5 * D_{dl}, where D_{dl} is the diameter of a disk containing 86.5% of energy of the spot produced by focusing an ideal supergaussian beam with equivalent beam size.

[15] At the aperture size of the final power amplifier; precise location of the wavefront correction is left to the Supplier.

[16] In single aperture; the conversion capability must be demonstrated on subscale aperture, with size of at least 5 cm, using crystal(s) and same fluence that can be used with nominal aperture to reach the design energy; the 3^{rd} and 2^{nd} harmonic beams are not required to be operated at the same time and full aperture crystals are not required to be part of the delivery.

[17] Net footprint of the main laser beamline, excluding space for HV capacitors and for the compressor (given by the space available in the ELI-Beamlines laser hall)

2.3 General technical requirements

The proposed solution for the delivery and commissioning of the kilojoule laser for 10 PW beamline operating at augmented shot rate must meet the following criteria:

a) The laser chain must be protected by optical isolation against undesired back propagation of light reflected from the target.

b) The laser chain must be delivered with deformable mirror (assumed at the level of the final power amplifier), operating within a closed loop supplied with data from a wavefront sensor. The closed loop must be an integral part of the delivered system.

c) The laser beamline shall operate in the cleanliness environment Class 10,000 (ISO 7), at temperature 21° C with long-term stability +/- 0.5° C, and at humidity 40 to 60% RH (see Section 5, ELI-Beamlines building environmental conditions and services).

d) The beamline should use cooling water available at the ELI-Beamlines facility (see Section 5 below, ELI-Beamlines building environmental conditions and services) as the ultimate heat sink and minimize heat rejection to the air.

e) The proposed solution must allow external pulse synchronization (see below External synchronization).

f) Fully automated control system must allow daily operation launched and remotely controlled from a single control room.

g) The proposed solution shall include machine safety controls (fail-safe mode) which allow stopping laser operation after one failed shot and which are sufficient to ensure routine and robust operation at full energy and protection of major optical components.

h) The system must be capable of uninterrupted operation for 8 hours a day and of over 200 workdays without significant performance degradation and without the need for major maintenance.

Meeting all the above mentioned requirements must either be clearly apparent from the description of the laser beamline or must be explicitly described in the proposal documentation.

2.4 Other technical requirements

2.4.1 Beam and pulse diagnostics

The laser beamline shall be equipped with full spatial beam and pulse diagnostic capability, sufficient to demonstrate that it meets requirements on the laser performance. The diagnostics, including far field and near field monitors, shall be deployed at least at the output of each amplifier. Apart from the final output beam the diagnostic array must include monitoring of the performance of the pump devices.

2.4.2 Pulse stretcher

The delivered system must include a pulse stretcher to produce nanosecond-class CPA pulses from the short-pulse oscillator. It is asked that the stretcher design is adapted to baseline design of the 10 PW pulse compressor. The dispersion management system must enable adjusting the compressed pulse duration at full output energy in a way to introduce minimum high orders of dispersion as possible.

2.4.3 Pulse compressor

Optical design of the 10 PW compressor has to be based on pulse energy before compression of at least 1.5 kJ. The optical design should feature compressor length of max. 12 m to make it compatible with the layout of the ELI-Beamlines facility. The proposed optical design should provide sufficient margin and robustness with respect to the maximum energy fluence on the gratings.

2.4.4 External synchronization capability

The front end oscillator must be capable of locking to an external master clock with precision of 10 fs or better. This master clock (a reference optical pulse train) at ELI-Beamlines will be produced by Er:fibre oscillator running at 240 MHz and pulse durations of roughly 200 fs. The oscillator must have an input for the error signal to correct the changes of the pulse repetition frequency of the oscillator output relative to the master clock. Details and parameters of interfacing between the clock and the oscillator will be discussed during the negotiation phase. ELI-Beamlines will also provide a configurable electronic timing system capable of generating external trigger pulses synchronized to the master clock with pulse jitter below 15 ps. It is required that additionally to autonomous operation of the laser any pulse pickers and pump lasers in the front end can be externally triggered by this electronic timing system in order to enable required timing of the output pulse. Details of interfacing of the external trigger signals with the laser will be discussed during the negotiation phase.

2.4.5 Local control system

The kJ class laser chain must be delivered with its own control system. The control system must provide interface that will allow porting of important process variables (PV) of the laser beamline and its control system into the central control system of the ELI-Beamlines facility. The Supplier is invited to use expertise of ELI-Beamlines in cooperating and/or supplying elements of the local control system and of the timing system. The Supplier will be required to prepare an interface control system document in cooperation with ELI-Beamlines within the early design phase of the laser to be built and delivered.

3. ELI-Beamlines building environmental conditions and services

Environment

3.1.1 The system must operate in the cleanliness environment Class 10,000 (ISO 7), at temperature 21° C with long-term stability +/- 0.5° C, and at humidity 40 to 60% RH. If operation of some subsystems require local cleanliness class higher than 10,000, local compartment(s) for ensuring this increased cleanliness class must be included in the delivery.

3.1.2 The proposed solution must feature integration of the laser system either to the ELI-Beamlines laser hall L4a and to the adjacent capacitor room (see Figure 2) located in the first floor, or to the laser hall L4b located in the ground floor (dimensions of this hall are identical to those of the hall L4a, indicated in Figure 2).

Power supplies

3.1.3 The maximum available electrical power supply capacity in the laser hall clean room environment is 150 kW (distributed as 230 V/ 50 Hz single phase and/or 400 V /50 Hz 3-phase European standard). The bid must involve a description of the facility requirements for the electrical power.

Cooling

3.1.4 The system must be able to use for primary cooling the cooling water circuit available at ELI-Beamlines, providing 20° C de-mineralized and de-ionized water. The needs for cooling water must be described in the bid.

Utility gases

3.1.5 The system may use as utility a clean dry compressed air (pressure 10 bar, oil <0.01mg/m^3, meeting ISO 8573-1 standard) available across the ELI-Beamlines facility. The needs for clean dry compressed air must be described in the bid.

Central vacuum

3.1.6 The primary vacuum (about 10^{-2} mbar) will be available at ELI-Beamlines from a central base-build distribution, and consequently supply of primary vacuum pumps is not required as a part of the delivery. Pumping speed of the roughing pumps used will be typically 450 m^3/h.

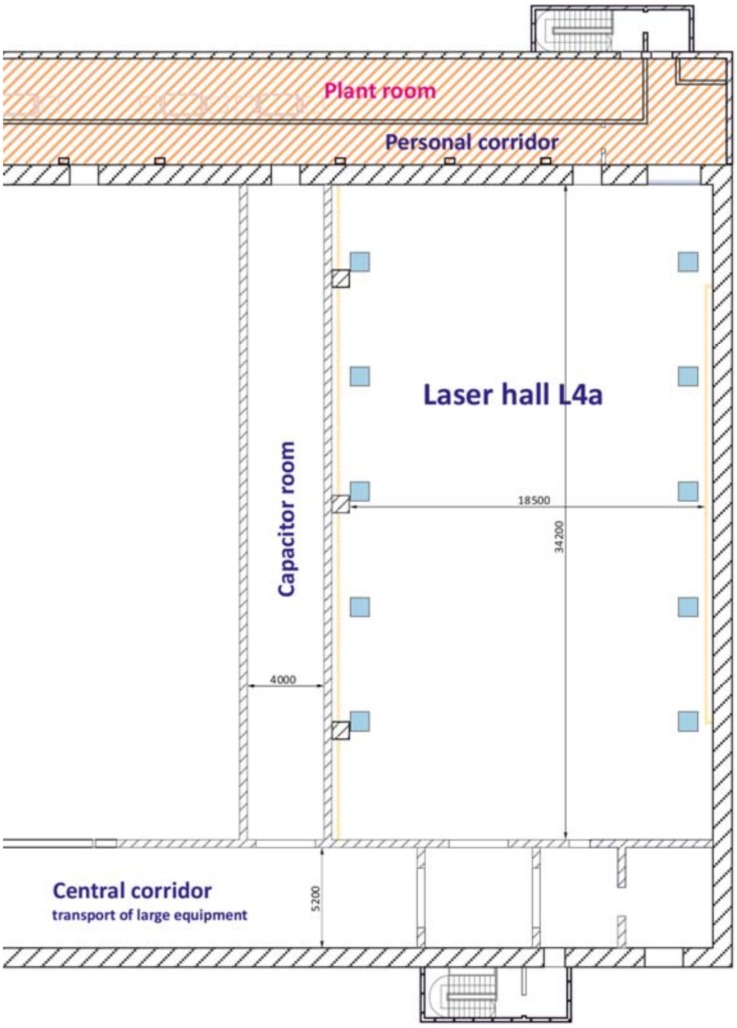


Figure 2. Layout of the laser hall L4a and of the adjacent capacitor room of ELI-Beamlines, projected to host the kilojoule laser system in the laser building; alternatively the L4b laser hall (with identical dimensions as L4a) can be used as well. The pulse will be sent to the experimental halls and/or to the pulse compressor room, situated in the below floor, by floor/ceiling penetrations (indicated in blue).