

Feasibility study for the

Scientific Case of the

ELI Attosecond Light Pulse Source,

Hungary

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ELI-Hu Nonprofit Kft.

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1. Introduction

The primary mission of the Extreme Light Infrastructure Attosecond Light Pulse Source (ELI-ALPS) Research Infrastructure is to provide the international scientific community with a broad range of ultrafast light sources, especially with coherent XUV and X-ray radiation, including single attosecond pulses. The secondary purpose is to contribute to the scientific and technological development towards generating 200 PW pulses, being the ultimate goal of the ELI project. ELI-ALPS, to be built in Szeged, Hungary, will be operated also as a user facility and hence serve basic and applied research goals in physical, chemical, material and biomedical sciences as well as industrial applications. The foundations of ELI-ALPS have been laid down by the ELI Preparatory Phase Consortium during the preparation phase of the project.

In the following a brief summary is given on the current status of planning the ELI-ALPS facility (Fig. 1), which also incorporates the proposals of the ELI ALPS 1st Scientific Workshop held in July 2010 in Budapest, and the suggestions at various discussions held with colleagues at CLF (RAL), MPQ, MBI, and also during the ECLIM Conference in Budapest and the ICUIL in Watkins Glen. Further discussions especially in ILE-ENSTA, CUSBO, FORTH and other knowledge centres in EU will further refine the planning. Once the technical and scientific cases are established, design details will be worked out together with internationally acknowledged experts for the submission of the proposal to the EU Structural Funds.

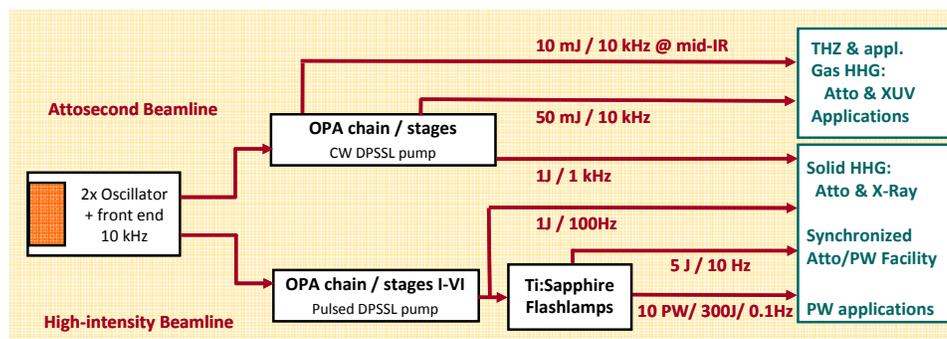


Figure 1. Current schematics of the laser systems of the ELI-ALPS Research Infrastructure with a list of secondary sources and applications.

2. Attosecond Beamlines

To fulfill the primary mission of ELI-ALPS, PW class driving lasers providing few cycle, CEP stabilised laser pulses are necessary to be operated at unprecedentedly high repetition rate. These pulses enable the utilization of all known methods of attosecond pulse generation. i) The well-established high harmonic generation in rare gases (GHHG) will be pushed to its ultimate limits by a loose focusing geometry, aiming at producing attosecond pulses with tens of μJ pulse energy. ii) It is anticipated that much more energetic and shorter attosecond pulses can be generated on solid surfaces (SHHG) reaching the X-ray domain. This method is not yet fully explored, so research will also be directed for the full exploitation of the technique. These two methods are offering complementary parameters to deliver a versatile atto-source for users. New methods of attosecond pulse generation utilizing field enhancement at nanostructured surfaces or dc-like external fields will be tested to enhance the generation process of attosecond pulses. Partly for this purpose, intense, synchronized THz pulses will be generated and their use for atto pulse generation will be implemented.

The Attosecond Beamlines of ELI-ALPS will thus offer a unique combination of various photon sources for multi-colour pump-probe experiments: spanning the spectrum from the THz to the X-ray range, with ultrashort pulse durations down to few cycles. The planned laser system will also provide a record breaking photon flux available in attosecond pulses, as well as the shortest wavelengths for attoscience applications.

The Attosecond Beamline will partly serve as a user facility. For this purpose, a well-established and reliable source has to be provided, i.e. GHHG pulses will be offered to users directly from the beginning and SHHG pulses shall follow with the improvement of corresponding technologies. ELI ALPS will offer both broadband, isolated attosecond pulses, using temporal or spectral gating techniques and quasi-monochromatic, strong femtosecond XUV pulses (isolated from the broad spectrum or generated with tailored GHHG techniques). A number of user stations will supplement the facility equipped for a set of spectroscopic and time-resolved experiments. The beamlines will open sequentially from 2015 on, starting with the GHHG beamline.

The HHG sources will be driven by laser pulses with different characteristics. For GHHG, loose focusing and high repetition rates are desirable. We propose a driver beamline that

will run at up to 10 kHz with few cycle pulses and up to 50 mJ. These sources (first run at moderate pulse energy) will operate as a facility for users; continuously improved with the advance of technology. SHHG will operate according to the results of a technology assessment procedure. Depending on the state of the art in 2015, this will either start immediately as a user facility, or as a test beamline. This beamline will be driven by laser pulses at 10 Hz...1 kHz with the highest pulse energies from the laser sources.

User applications of the femto- and attosecond X-ray pulses, produced via high harmonic generation, span a wide range including fundamental time-resolved and structural studies, Coulomb explosion imaging of large molecules and clusters, attosecond metrology, attosecond and ultrafast X-ray spectroscopy as well as diffraction imaging. These sources will provide tools to probe electron dynamics in atoms, molecules, and solids with sub-femtosecond temporal resolution, or will be used in plasma diagnostics and single molecule imaging in time-resolved microscopic studies.

2.1. High-order harmonic generation schemes

A fundamental limit on the achievable pulse duration for a light source is given by the period of the carrier component of the radiation. Lasers operating in the visible and infrared spectral region are limited to pulse durations of a few femtoseconds. To reach the attosecond regime the coherent radiation has to be extended to shorter wavelengths.

Almost 20 years ago, high-order harmonic generation in gases (GHHG), which transforms the desirable laser characteristics to higher frequencies, providing coherent radiation over a large spectral bandwidth in the XUV range, was proposed as a possible candidate for the production of attosecond pulse trains. With the increase of achievable laser pulse energies an alternative method, high-order harmonic generation on solid surfaces, has been proposed and demonstrated to yield even broader XUV and X-ray radiation. Attosecond pulse production at ELI-ALPS will be based on these two processes.

2.1.1 High-order harmonic generation in gases (GHHG)

When an ultrashort laser pulse is focused into a rare gas, achieving intensities of the order of $10^{14}\sim 10^{15}\text{W/cm}^2$, the atomic potential is considerably distorted, and electrons can tunnel out to the continuum (Fig. 2). The free electron is then accelerated by the laser field first away from the

nucleus, and when the electric field changes sign, towards the nucleus. If the driving field is linearly polarised, there is a probability of the electron being recaptured by the ion, in which case the kinetic energy gained from the laser field is emitted in form of a high energy photon.

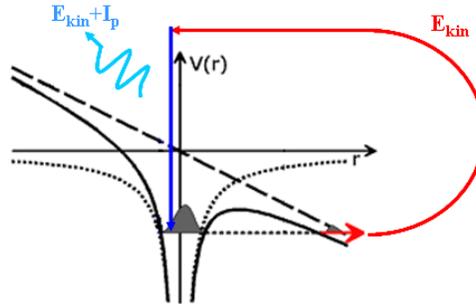


Figure 2. GHHG principle

A typical harmonic spectrum – consisting of peaks separated by twice the laser frequency – contains an extensive plateau of almost constant amplitudes, that ends in an abrupt cut-off corresponding to the maximum energy the electron can gain in the continuum. It was realised shortly after the discovery of HHG, that the broad frequency range of the plateau harmonics would support pulses of sub-femtosecond duration. The periodic structuring of the spectrum – when translated to the time domain – suggests, that a train of attosecond bursts, rather than a single pulse, might be produced, reflecting the process appearing every half-cycle of the laser pulse.

Isolating a single attosecond pulse from this pulse train is a challenge, as well as a necessity for clean analysis of pump-probe experiments. There are two methods proposed and demonstrated to meet this aim, i.e. to confine harmonic emission to a single half-cycle of the driving laser pulse. The first method is based on driving the process with a few-cycle driving pulse, and hence the generation of the highest harmonics is naturally confined to the peak half-cycle. By spectral selection of these highest harmonics produce a single attosecond pulse. The other solution to the problem utilizes the fact that the efficiency of harmonic generation rapidly drops with increasing ellipticity of the driving field, so using a longer driving pulse with varying ellipticity, in a way that the pulse is linearly polarized only during the central half-cycle, leads also to the production of single attosecond pulses.

To increase the amount of the emitted high order harmonic radiation, one can increase the laser pulse energy, or attempt an improvement of the generating efficiency. There is a limit to which the generating intensity can be increased imposed by ionization of the medium: beyond a

level there will be no atoms left to participate in the harmonic generation process. The efficiency of high order harmonic generation is to a large extent determined by whether phase matching can be achieved in the medium or not. Phase matching can be greatly enhanced either by making the phase variation in the medium slow, or by making different phase-variations balance each other. An increase of the beam size, loose focusing and quasi-phase-matching techniques can increase the amount of produced HH radiation.

2.1.2. High order harmonic generation in a plasma produced on solid surfaces (SHHG)

The generation of coherent high harmonics from the interaction of an ultra-intense laser pulse with a solid density plasma surface has the potential of overcoming the limitation of the generating laser intensity observed in GHHG, and producing attosecond pulses of unprecedented intensities that could be applied to a wide range of experiments. Two distinct mechanisms for plasma surface high harmonic generation (SHHG) have been identified (see Fig. 3.). For relativistic laser intensities, i.e., when $I\lambda^2 > 1.38 \times 10^{18} \text{ Wcm}^{-2}\mu\text{m}^2$, the dominant process is the frequency up-shifting of the incident laser light due to the reflection from the relativistically oscillating electron density surface, termed as the relativistic oscillating mirror (ROM). For sub-relativistic and moderately relativistic intensities the dominant mechanism is the coherent wake emission (CWE).

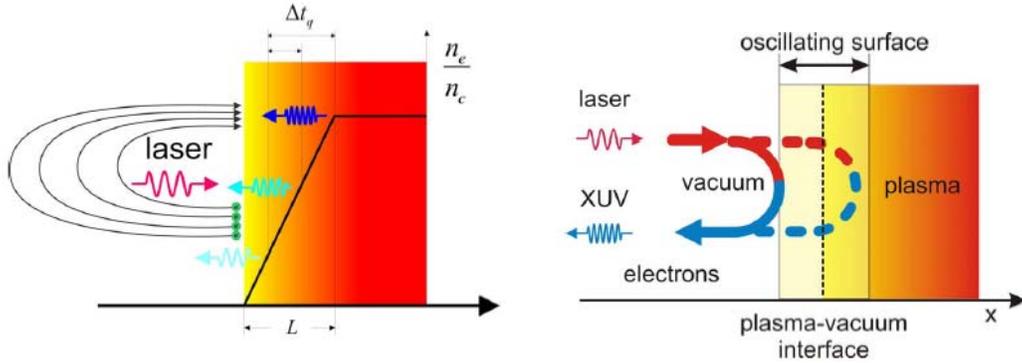


Figure 3. SHHG processes: Coherent Wake Emission and Relativistic Oscillating Mirror (Figure reproduced from G. Tzakiris talk at the 1st Scientific Workshop on ELI-ALPS)

Both of these mechanisms are expected to generate coherent harmonics leading to temporal bunching and the generation of attosecond bursts of XUV radiation. Many recent experiments have increased our understanding for both SHHG mechanisms. Harmonic spectra extending up to the keV photon energy range (approximately the 2800th order of the fundamental laser frequency), and the generation of diffraction limited harmonic beams at 40 nm wavelength has

been presented. An order of magnitude higher conversion efficiency in SHHG than in GHHG was also demonstrated. Using the technique of the second-order volume autocorrelation, a subfemtosecond temporal structure was observed.

Experiments so far have focused on characterizing the generated harmonics. If one wants to take surface harmonics to the next level, i.e., to use the generated radiation in a variety of applications, it becomes important to study issues such as transporting the beam, filtering the spectrum, suppressing the reflected infrared (IR) light from the target and increase the repetition rate to allow accumulation of many shots. Coherent broadband radiation down to 15 nm, capable to support synthesis of single pulses of 120 asec duration, and energy content in the sub-100 nJ range has been lately measured.

2.1.3. Comparison of generation schemes

Both HHG schemes have certain advantages and disadvantages over the other. Current assessment is summarized in the Table 1, while the currently available attosecond pulse parameters and the predictions for ELI-ALPS are summarized in Table 2.

Gas medium	Plasma medium
Simple generation setup	More complicated setup
Well understood / controlled mechanism	So far less control on the generating process
High replate operation	Currently only low rep rate achieved
Small divergence	Large divergence
Low efficiency	Higher efficiency
Generating laser intensity limitation	No laser intensity limitation
Limited to sub-keV range	Extendable towards shorter wavelength

Table 1. Comparison of attosecond pulse generation processes (Table reproduced from G. Tzakiris talk at the 1st Scientific Workshop on ELI-ALPS)

Source	Spectral range	Duration	Pulse energy at source	Peak intensity at target
GHHG single pulse	20-100 eV	100 asec	1 nJ	10^{11} W/cm ²
GHHG pulse trains	10-100 eV	100 asec 10 fs envelope	1 μ J	10^{14} W/cm ²
SHHG current status	10s eV - few keV	900 asec 40 fs envelope	1 μ J	10^{12} W/cm ²
SHHG predictions (ELI)	10s eV - few keV	100-5 asec	100 mJ	10^{23} W/cm ²

Table 2. Present and predicted characteristics of attosecond pulses (Table reproduced from G. Tzakiris talk at the 1st Scientific Workshop on ELI-ALPS)

2.1.4. Monochromatised XUV beams

Additionally to the attosecond range XUV beams, ELI-ALPS will offer monochromatised XUV pulses to users for a wide range of applications. From the broad spectrum of XUV radiation produced by high-order harmonic generation it is possible to isolate a single harmonic using a specially designed, time-preserving monochromator. This yields short (fs range) and tunable narrow-bandwidth XUV pulses, for ultrafast dynamics experiments spanning gas-phase chemistry, condensed-matter physics of complex materials.

2.1.5 THz assisted atto pulses

A recently proposed scheme for attosecond pulse generation relies on GHHG in presence of a strong dc or quasi-static electric field. The electric field interacting with the atom is increased in every second half-cycle, thus enabling the generation of higher-order harmonics, and as a consequence, attosecond pulse shortening. It also attributes to a break of symmetry between the half cycles, and thus reduces the number of attosecond bursts, helping the isolation of a single attosecond pulse. For a pronounced effect the electric field vector of the applied quasi-static field has to be extremely strong, on the order of (several) tens of MV/cm. The tremendous progress of the last few years in the generation of intense ultrafast THz radiation driven by femtosecond laser pulses has opened up the way towards achieving such extremely high field strengths. Optimized high-intensity THz sources will require infrared pump wavelengths in the range of 1.5 – 2 μm or even longer. In order to facilitate experiments requiring extremely high THz field strength, and to allow utilization of the advantageous scaling properties of HHG with increasing wavelength, an IR beamline is planned together with HHG and THz generation stages.

2.2. Implementation (layout)

In ELI-ALPS, attosecond bursts will be produced with laser pulses coupled out at various stages of the laser amplification chain. Both GHHG and SHHG processes will be utilized best suited for user specifications of the desired source. It is envisaged that the GHHG source working at 10 kHz and a moderate pulse energy will run as a user facility from the start of the ELI facility, whereas other attosecond sources will probably open in due time following technological advances.

We propose alternative HHG setups (see Figs 4 & 5).

i) the high-reprate (10 kHz) arrangement will generate attosecond pulses at a moderate pulse energy, using medium range focusing. Few mJ pulses – synchronized with THz pulses or (2nd, 3rd) harmonics of the IR laser pulse – will be focused into a static gas cell. The attosecond pulses – after filtering and/or recombination with the generating beam – will be refocused by a toroidal mirror for applications or characterization.

ii) loose focused GHHG will be implemented for higher generating pulse energies. Combinations with laser harmonics or THz pulses for this arrangement will also be enabled. For this scheme the possibility of harmonic generation in multiple gas jets – utilizing quasi phase-matching – will also be incorporated.

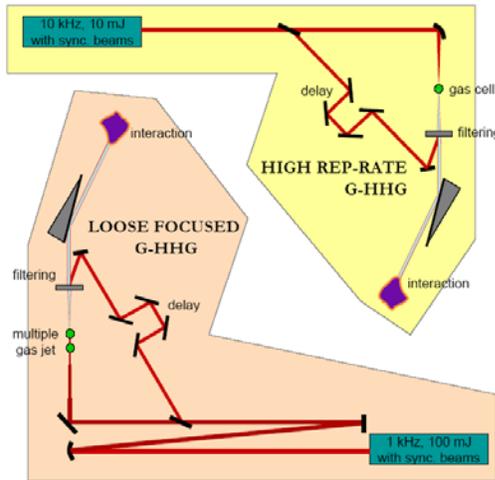


Figure 4. GHHG schemes

iii) plasma harmonics will be produced in a tight focusing geometry at gradual increase of the repetition rate with the advance of technology. In this arrangement the suppression of the IR beam traveling collinear with the harmonics shall pose a major challenge.

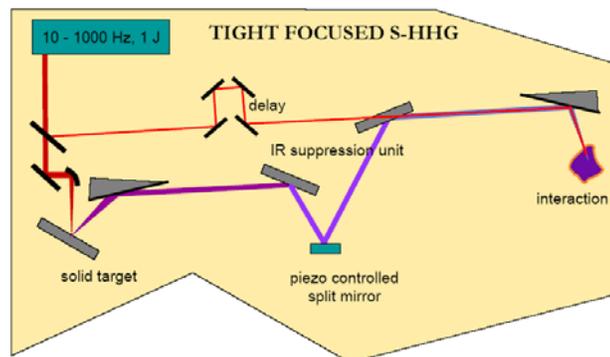


Figure 5. SHHG scheme

2.3. XUV beam handling

Attosecond pulses occupy the XUV and X-ray region of the electromagnetic spectrum. To apply these pulses to their full potential, beam handling (such as steering, beam splitting, focusing, compression, angular dispersion elements), pulse shaping and the characterisation techniques already known for femtosecond pulses need to be transformed to the new wavelength region.

2.4. Attosecond pulse characterization

Pulse characterization in the fs domain rely on nonlinear optical phenomena, not directly translatable to the XUV. Presently there are both autocorrelation and cross-correlation (with IR) techniques used for attosecond pulse characterization.

2.5. Applications

The laser beam delivery will be configured with high flexibility to allow generation of broadband or monochromatised XUV with a wide range of laser pulses. Also combinations with laser and secondary sources for pump-probe studies will be enabled. The combination of beamlines will be arranged as required by the specific user experiments.

3. High-Intensity Beamline

3.1 Introduction

To meet the mission of ELI-ALPS as a world-leading center for multidisciplinary research, a high-intensity beamline is also required. The driver laser chain is planned to reach a peak power of about 10 PW at a moderate repetition rate of 0.1 Hz (more details are given in Section 4 on the primary sources). The applications will exploit the unprecedented flexibility offered by the laser and secondary source parameters in terms of repetition rate, wavelength (spanning the electromagnetic spectrum from THz to X-rays), pulse duration (from femtosecond to attosecond) etc. Besides of providing the possibility of multi-color, modular light, radiation and particle sources and a high level of European user accessibility, special care is to be devoted to offer services of the highest standard for users in terms of in-house expertise, diagnostics, target fabrication, electronic and mechanical workshops and providing a standard set of high-quality equipment. These features would distinguish the 10 PW beamline of ELI-ALPS among the other national 10 PW lasers, which are likely to start operating also around 2015.

Once this high intensity beamline is established, independent experimental studies are also planned directly with the laser pulses or indirectly with generation of other secondary sources. Besides the research on different amplification schemes, coherent beam combination experiments will be carried out to assess technologies for the final ELI goal of a 200 PW facility.

3.2 Sources based on the high-intensity beamline

The high-intensity beamline will serve as a driver source for versatile radiation and particle secondary sources. The unique feature of these sources will be their broad spectrum in terms of available photon and particle energy. Particularly, ultra-bright sources of high-energy radiation will be available also for users. Also, different stages of the laser chain will be directed to various output ports. The following group of sources is planned:

3.2.1 Short wavelength radiation sources

Femto- and attosecond X-ray pulses will be generated via solid high harmonic generation (SHHG) detailed in Section 2 above. These efforts will be focused on both source development

(investigating scaling laws, optimizing targets for high repetition rate operation etc.) and on constructing a user access source based on the state-of-the-art of SHHG technology.

There is a strong need from the users for x-ray sources with ultrahigh intensity, photon energy on the multi-keV (10 keV) scale, and fs or sub-fs temporal resolution. Such sources have promising applications in many fields of science and technology, such as structural biology, medicine, materials sciences, time-resolved structural studies, etc. Laser-driven x-ray sources allow good complementarity with accelerator-based sources. Currently, only gas HHG is sufficiently developed for being suitable for user facility operation. However, the available photon energy is limited (< 3 keV), which limits application possibilities. Other promising x-ray sources, such as x-ray free-electron lasers driven by laser-accelerated electron beams or Thomson scattering, can produce higher photon energies. However, currently these techniques are at the proof-of-principle stage. Once the high-intensity beamline is operational, reliable x-ray sources will be implemented as user facilities, depending on the progress of technology development.

3.2.2 Particle beams

Ultrafast particles (electrons, protons and ions) will be generated to serve fundamental and applied research as well as biomedical applications. The distinctive feature of the Szeged facility will be the presence of the few-cycle driver laser of the attosecond beamline with 1 J pulse energy and 1 kHz repetition rate. This enables high repetition rate particle (especially electron) acceleration experiments that would be highly interesting for a number of groups active in the field of laser plasmas and particle physics. Additionally, because of the synchronization possibility with the attosecond driver beamline, generation of more “standard”, low-repetition rate secondary particle sources in the high intensity beamline should not be excluded but the main emphasis will be put on user accessibility and not on source development. Therefore, state-of-the-art of user-accessible secondary source options will have to be re-assessed in 2013 to enable the finalization of the target areas of the high-intensity beamline. Potential users in medicine, ultrafast science and industry will be contacted in due course to assess user interest and finalize source requirements. This way, experiments aiming at applications such as the hadron therapy of cancer with energetic particle beams will also be made possible. This means

that particle acceleration target areas will be fed by both the attosecond driver and the high intensity beamlines depending on the secondary source requirement for the given application.

3.2.3 Laser output ports

The focused ultrahigh-intensity laser pulses will also be available for fundamental (partially time-resolved) studies of laser plasma interactions and exotic physics applications. The goals here will be partly technological since novel focusing and coherent beam combination methods will also be investigated in order to exploit the full power of the 10 PW beam to produce the highest focused intensities.

3.3 Experiments with primary and secondary sources of the high-intensity beamline

The distribution of the target areas will offer unique possibilities for the combination of laser beams from all parts of the facility. Hence, a versatile beam delivery matrix is to be designed in order to maximize functionality and flexibility for unique experiments with multi-source inputs. Ongoing discussions with experts and potential users will clarify the desired parameters of secondary sources of high-energy particle beams and ultrashort pulsed electromagnetic radiation spanning the THz to X-ray spectral domain. The specifications will include the necessary laser parameters for each secondary source (intensity, pulse shape and length, contrast, repetition rate etc.) as well as the feasible secondary source parameters.

Primary laser sources from the amplifier chain (both split-out and final stage beams) will be used either by source development units of SHHG (see Section 2), high repetition rate electron beams and low repetition rate electron and proton/ion beams. The main development issues to be solved here will be the construction, optimization and benchmarking of a suitable target for SHHG and high repetition rate electron beams, therefore dedicated areas will be made accessible for these purposes.

A user accessible SHHG source with a number of user stations can also be based on the high intensity beamline since the output of lower repetition rate duty amplifiers will enable less demanding target solutions. Therefore, user experiments in the fields of physics, material science and biology are envisaged with femto- and attosecond X-rays with $> 3\text{-}4$ keV photon energy using outputs of the high-intensity beamline.

4. Target areas

Here the design principles of beam delivery system and the target areas (TAs) are outlined. A schematic layout of the TAs will also be given. In general, the course of compiling the ELI-ALPS White Book will allow discussions on the still open questions and finalize the high intensity beamline and target areas layout.

4.1 Design criteria for the target areas

In order to make possible time-resolved pump-probe studies with a wide range of radiation and particle sources, a set of design criteria has been established.

4.1.1 Modularity

The layout of the target areas should offer the highest degree of modularity in terms of secondary source and user station layout. Since the installation of secondary source target chambers and the subsequent user stations will take place in 2015, one has to consider the option of complying with those secondary source generation schemes that are currently not fully developed. This is especially important in the field of high repetition rate (100 Hz...1 kHz) particle acceleration and related radiation sources. Target areas should also offer further extendibility including blind vacuum ports for chamber extensions and additional user stations, movable radiation shielding units etc. Details of these engineering solutions will have to be worked out during the design phase by a joint national and international engineering team having experience in the construction, extension and operation of large-scale research facilities.

4.1.2 Flexible laser beam delivery system

A sophisticated laser beam delivery system will have to be developed in order to enable laser beams at different amplifier stages of both beamlines to be transported into different target areas. A typical example of this requirement is SHHG source development experiments described in section 2, where driver laser pulses from both the attosecond laser and the high-intensity laser beamline should be available. As for which driver source will be utilized will highly depend on the repetition rate of the laser source that can be used for the SHH generation. The optimum repetition rate for this application is highly dependent on the solution of renewing the target.

Several leading groups are intensively working on different schemes to find a suitable target for high repetition rate SHHG. One can only determine the suitable repetition rate for these experiments after knowing the actual status of these projects in 2014. Therefore, the laser and experimental halls including the target areas will have to be planned with suitable, complex beam delivery systems and later flexibility.

Another example is the generation of high repetition rate electron beams (possibly with 1 kHz repetition rate). Here, the electron acceleration experiments will be first tested with a lower repetition rate split-out from the high-intensity beamline, whereas full source specifications will be achieved with the final duty output of the attosecond driver beamline.

Therefore, it is foreseen that laser pulses of various energy level and repetition rate will be coupled out after each major amplification stage of the high-intensity, 10 PW laser chain, and steered towards the target areas. Since some split-outs in the chain may require separate laser pulse vacuum compressors, the exact outcoupling positions will be determined in due course according to the given application and user/industry requirements, to be assessed during the preparatory phase of the ELI ALPS project with the help of international experts and prospective users.

4.1.3 Separated user access and R&D units

User access source units and source development units should be separated to allow effective technology developments. Since the ELI-ALPS beamline facility will rely on cutting-edge technology, besides scientific experiments with existing sources also emphasis is put on source development. It is currently especially the attosecond community in Europe that is involved in the source development efforts in ELI ALPS. Source development of other secondary sources that are not primarily attosecond sources, such as particles, free-electron laser based radiation sources etc. will be the main task of the Czech ELI facility. However, because of the synchronization possibility with the attosecond driver beamline, generation of these other types of secondary sources in the high intensity beamline should not be excluded but the main emphasis will be put on user accessibility and not on source development. Therefore, state-of-the-art of user-accessible secondary source options will have to be re-assessed in 2013 to enable the finalization of the target areas of the high-intensity beamline.

4.1.4 Synchronised beams from the two laser beamlines

Synchronized input from both laser beamlines should be possible. This will be enabled by running both beamlines from a single front end (which would be one of the identical, duplicated front ends of the facility, see Chapter 5). Further active and passive measures will have to be taken to enable synchronization between the beamlines including vibration isolation of the building, the optical tables and component mounts, the full enclosure of beam paths, active path length stabilization in different laser units, temperature stabilization of the experimental halls etc.

4.1.5 Target areas with different radiation protection

It is necessary to differentiate between the target areas and experiments with respect to the level of necessary radiation protection, beam dumps etc.. The less demanding TAs will enable a more versatile layout that can be reconfigured more easily for different types of experiments. Target areas for electron acceleration will necessitate complex measures for beam dumping and shielding which will also be made as flexible as possible within the available limits (see Chapter 4.4).

4.2 Target area layout

The beam distribution and the layout of the target areas are determined by the number of the outcoupled laser beams, their output parameters, and the desired secondary sources. As discussed in Section 5, besides the laser chain depicted in Fig.1 alternative schemes are also considered. As the TA layout strongly depends on the design of the laser chains, various alternatives may have to be considered for the TA design, too. However, there are also features, which are independent of the details of the laser design.

A TA layout corresponding to the laser system described in Fig 1 is shown in Figure 6. According to the expected radiation dose and the required shielding three groups of target areas are identified.

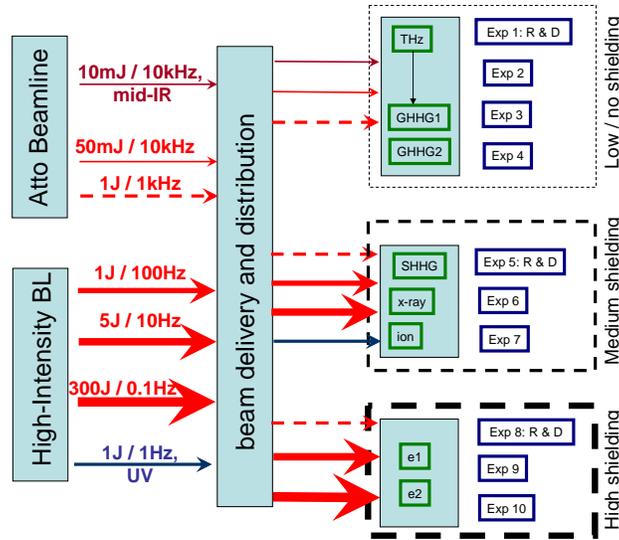


Figure 6. Layout of the target areas.
The indicated laser parameters are compatible with the laser scheme in Figure 1..

- i) Experiments with no radiation hazard can be carried out in the **non-shielded environment**, which is also the most flexible in terms of experimental arrangement and beamtime distribution. The secondary sources available in these TAs include GHHG sources with moderate photon energy and longer wavelength radiation such as THz and IR. One of the GHHG sources uses medium focusing, the other loose focusing. The GHHG sources can be used stand-alone, in combination with the driving laser sources or in combination with the THz source (for THz-assisted attosecond generation). In addition to this, the high-intensity THz source can also be used stand-alone or in combination with the driving laser pulses.
- ii) Experiments producing low radiation doses can be carried out in the **group of TAs with moderate shielding**. In this case we will try to maintain maximum possible flexibility by using movable (non-permanent) shielding walls and shielding blocks. The reconfiguration of the shielding in one of the experimental stages will not affect work at the other stages. These assumption will be verified by radiation protection simulations during the preparatory planning phase of the ELI-ALPS facility. The secondary sources available in these areas are high-photon-energy x-ray sources (surface-HHG, and possibly also incoherent x-ray radiation) and sources of laser-accelerated protons and ions. Also pulses from the driving lasers will be available for pump-probe type studies in the experimental chambers.

- iii) Experiments, primarily on laser-accelerated electrons, with high radiation risk will be located in the **highly protected TAs**. A key feature will be the availability of kHz-repetition-rate electron bunches besides electron sources with large bunch charge or higher energy but with lower repetition rate (10 Hz or 0.1 Hz). This requires the availability of (at least one of) the attosecond beamline(s) as well as that of the high-intensity beamline for electron acceleration. To allow fully independent work at the experimental stages the shielding geometry should allow access to all of the experimental stages while experiments are running at any stage(s). Knowing proposed multi-component beam dump and shielding solutions discussed in WP6 of ELI-PP, fulfilling these requirements can be a substantial challenge.

According to this classification, around three experimental areas are planned at each level of shielding, in accordance with the general principles given in Section 4.1. The four experimental areas in the non-shielded TAs may allow for more flexibility in experiments and in combination of (primary and secondary) sources. In each group of TAs one of the experimental areas is devoted to source development supporting future updates of the secondary sources and the implementation of new technologies.

4.3 Instrumentation

Target area instrumentation will be provided for user and source development groups using the facility. This will include standardized vacuum elements, pumps, control systems and instrumentation (gauges, signal processing electronics, amplifiers, oscilloscopes etc.) to be worked out together with the Czech and Romanian facility teams. The availability of diagnostics tools especially for the secondary sources are of crucial importance for the user experiments. Since such devices or setups are integral and indispensable parts of all experiments the detailed design of the secondary-source/experimental chambers should take this requirement into account. Some of the diagnostic tools might need considerable space (e.g. electron spectrometer) or additional chambers, therefore they may effect the design of the target areas, too.

We also plan to set up a state-of-the-art target fabrication laboratory to enable the generation of targets for demanding applications for high repetition rate laser sources. Auxiliary

service units for staff and users will include a chemistry laboratory, a mechanical and an electronic workshop and a computer facility specializing in measurement data acquisition and evaluation as well as laser, safety and target area control systems. The latter group will both develop control interfaces for daily operation and serve user needs during specific experimental campaigns.

4.4 Radiation protection

As already mentioned in Section 4.2, radiation protection in the target areas is a key issue. An international expert team will be organized at an early stage of planning the ELI-ALPS infrastructure to deal with this challenge. During the planning phase there will be continuous interaction between source design, building design and radiation protection experts. The radiation protection system shall be fitted to the requirements of highest flexibility in user facilities. Modular and flexible shielding blocks will be used. Results of the meetings and discussions within Workpackage 6 of the ELI Preparatory Phase activities are particularly valuable for this purpose. The expertise from other fields of science such as that from synchrotron and accelerator community should be utilized as well.

Radiation protection measures will be planned according to the ALARA principle (as low as reasonably achievable). This means that the justifiable radiation exposures resulting from practice must be reduced to the lowest level possible considering the cost of such a reduction in dose. One must also take into account and enforce dose limits which involves setting upper limits on the dose that may be received by any member of the institute from all man-made exposures other than medical exposures.

After determining the laser input parameters, one can simulate light-matter interaction and the generated particles with the OSIRIS code including energetic electrons, protons, ions, muons etc. After this, beam dumps and shielding elements can be designed with the FLUKA code. Some sophisticated beam dump solutions have already been developed for the Czech ELI facility, the results of which can be optimally utilized and adapted to the target areas of the ELI ALPS facility. One also has to consider the possible activation of shielding materials and carry out life cycle analysis. Particles generated during high-intensity light-matter interactions can also activate air, water and solid materials which has to be considered in the building engineering

designs, especially in that of venting and heating of the experimental halls. Extraordinary events, such as unexpected power loss resulting in the switching off of guide magnets and short-lived particle beams hitting the vacuum chamber walls etc. also have to be considered. During normal operation particle beams will be absorbed by a complex and individually designed system of beam dumps and shielding layers made up of multiple materials including steel, graphite, borated polyethylene and concrete. The activation of shielding materials has to be considered and it has to be determined with preliminary calculations what is the amount and handling procedure of potential nuclear waste produced in the facility.

The facility must be equipped with a full radiation protection monitoring system including active and passive detectors and counters. By the time of facility commissioning, staff and user access rules to the target areas have to be determined in order to minimize exposure and training has to be provided for all those involved. Access to target areas will be possible only with an access control system that is connected to radiation monitoring devices. The facility premises and the environment also has to be controlled regularly and soil, water and vegetation samples have to be taken at nearby control points in order to determine potential exposure.

5. Primary light sources – laser chains

5.1 Introduction

Keeping in mind the request from the scientific case of the Facility, due to the very restricted time constraints, compromises are needed between a “dream beam”, requiring considerable R&D efforts, and a state-of-the-art solution, which relies on available industrial products. The margin is hence narrow: we need to industrially contract as many products and R&D tasks as feasible, and contract the scientific community (including ELI-ALPS itself) only to tasks which are scientifically challenging but industrially uneconomical. Thus, the basic aim of this chapter is to show and design systems, which satisfy the scientific demands, then analyse them how feasible is their implementation by December 31, 2015.

5.2 Version 1: a 5J / 1 kHz and 10 PW / 0.1 Hz dual laser chain

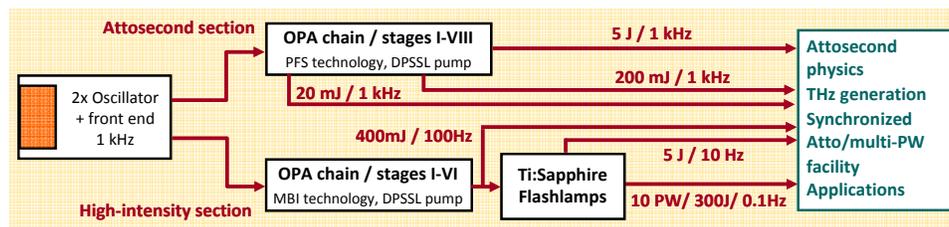


Figure 7. The initial schematics of the laser systems of the ELI-ALPS Research Infrastructure.

In order to satisfy all the basic design criteria driven by application of laser pulses, the scheme in Fig. 7 was first developed. The two laser beamlines will have identical early front ends, consisting of a carrier-envelope phase (CEP) stabilized, Ti:S based commercial laser system working at 800 nm and with 1 kHz repetition rate. The diode-pumped solid-state (DPSS) pump laser at 1.03 μm as well as a 1.5 μm satellite amplifier for THz generation will be fed by a part of the 5 mJ, sub-30 fs laser pulses. The seed pulses for both the attosecond driver chain at 900 nm central wavelength and for the 10-PW chain at 800 nm will be generated from the largest part of the commercial system through spectral broadening and subsequent cross-polarized wave generation (XPW) filtering, so that few cycle, high temporal contrast laser pulses enter the optical parametric chirped pulse amplification (OPCPA) stages.

The repetition rate and bandwidth of the pulses in the attosecond driver chain are expected to be kept at 1 kHz and >300 nm, respectively. The pump sources are based on DPSS laser technology, using cw diode lasers. The generated pulses at various energy levels are to be provided for HHG and attosecond generation and application, while the chain of 20 mJ laser pulses at 1.5 μm is primarily dedicated to THz generation.

The first OPCPA stages of the High Intensity Beamline will operate at 100 Hz repetition rate and pumped by pulsed diode based thin disk pump lasers. The subsequent power amplifiers are to utilize Ti:sapphire technology and are likely to be pumped by flashlamp-pumped Nd:YAG (10 Hz) and Nd:glass lasers (0.1Hz), providing higher pulse energies but limited to a lower repetition rate. An additional beamline at 248 nm, based on KrF laser technology, is also planned, so that laser sources would be directly available from UV to mid IR.

To ensure high nanosecond temporal contrast, the seed pulses to the duty end amplifiers have to be selected at about 0.1 J level. We have to mention that this scenario is held assuming that the development rate of DPSSL technology remains the same as today. However, if DPSSL technology speeds up and is likely to offer high energy pulses at higher repetition rate and lower cost, then it might happen that DPSSL lasers will be applied throughout the whole system, right from the beginning, instead of flashlamp pumped lasers.

Most of the major bottlenecks in laser technology have been identified and listed below. Solving these challenges during developments in the prototype projects of ELI is a prerequisite for the success of the ELI ALPS facility. The bottlenecks and scientific-technological challenges can be divided into two major classes. The first one consists of those involving mainly industrial R&D effort. The second one may require considerable scientific researches primarily from the academic R&D institutes.

5.3 Major bottlenecks and possible solutions – version 1

5.3.1 Industrial bottlenecks

11. kW class pump lasers at high repetition rate (2.5J @ 100Hz, 30J @ 1 kHz in IR)

At these repetition rates the diode pumped thin disk lasers could be the only efficient candidates. The highest achieved stable performance was reported to be 450mJ @ 100Hz (in MBI) and

25 mJ @ 3 kHz (in MPQ), both are working in close collaboration with Trumpf. It is very likely that these lasers will be successfully developed to reach 2J @ 100 Hz and 150mJ @ 3 kHz by the end of 2011. Additional efforts would be needed to further increase the energy of the pulses.

Expected performance by the end of 2013, assuming the current trends and efforts:

3 J @ 100Hz; 350mJ @ 1 kHz

Evaluation:

Since the amplifier stages at that level will be based on OPCPA, where two pump beams can be safely used to pump a single crystal (or two amplifier stages can be used in sequence), the 0.4J / 100Hz specification for the amplified pulses can be held.

The situation at 1 kHz seems more difficult, as the prediction is $25\times$ lower than the required single beam pump energy. A back-up solution would be then to use Ti:S technology, which has the advantage that even 10 pump beams can be imaged to the crystal, and double/triple pass amplification of the signal is the standard. In this case, however, *the bottleneck is the cooling of the Ti:S crystal*, since around 15kW heat shall be dissipated! However, it needs to be pointed out that aiming at this energy level represents a high risk!

Solutions – R&D directions:

Pump laser development (Trumpf, Jenoptik, MBI, MPQ, ...)

Crystal head / cryogenic cooling development (Thales, ...)

12. Broadband, low / high dispersion optical coatings

(>300 nm LDT>1J/cm², GDD flat < 50fs², and <-100 fs² size up to Ø=5 cm)

There are coatings available with broad bandwidth, low and high dispersion (e.g. Layertech, CVI, Optilab), but the laser damage threshold (LDT) is low (0.1 J/cm² for 30 fs pulses). Developments have been started to develop high damage threshold, low dispersion coatings with a relatively modest bandwidth of 100 nm (ILE, REOSC), while similar efforts are also planned at MPQ (Ultrafast Innovations GmbH).

Expected performance by the end of 2013, assuming the current trends and efforts:

LDT=0.5 J/cm², 100nm; LDT=0.3 J/cm², 200nm; LDT=0.2 J/cm², 300nm.

Evaluation:

It is very likely that suitable optics will be available for the high intensity beamline. For the attosecond beamline, however, extensive R&D needed to increase the LDT and keeping the bandwidth of the coatings.

The primary aim is, however, to keep the bandwidth and dispersion low. As a backup solution, hence the obstacle of low LDT can be overcome by increasing the beam size. Regarding that the mirrors at high repetition rate are safe to operate at a maximum of 20% fluence of their LDT, and taking the assumed LDT level expected above, mirror size of $\varnothing=17$ cm are needed (Rule of thumb: the optics size shall be three times the FWHM of the beam size to avoid diffraction effects of a Gaussian beam). At this size, however, the homogeneity and spectral phase shift of the surfaces are challenging.

Solutions – R&D directions:

Support research at industry towards high(er) damage threshold, broadband optics, and also towards producing current layer structures with high enough uniformity and quality in large size. (SAGEM REOSC, Leybold Optics, Ultrafast Innovations, etc.).

I3. Highly efficient (>90%) (dielectric) diffraction gratings for pulse compression with suitable bandwidth (>200 nm, 300nm) and laser damage threshold (1J/cm²);

There are gratings available with broad bandwidth, high efficiency, but the damage threshold is low (<0.07 J/cm² for 30 fs pulses). Promising developments have been going on to increase the damage threshold with the use of dielectric gratings, hybrid gold-dielectric gratings and metallic-dielectric gratings (Institute Fresnel, Jobin Yvon, SAGEM REOSC, Plymouth Grating Company).

Expected performance by the end of 2013, assuming the current trends and efforts:

LDT=0.2 J/cm², 200nm, $\eta>90\%$, LDT=0.15 J/cm², 300nm, $\eta>90\%$,

Evaluation:

It is very likely that by that time developed gratings would be just about sufficient for the high intensity beamline, so that gratings are needed at a size of 110cm×40cm. It would be more safe, however, if an LDT of 0.4 J/cm² was achieved. In this case the grating size could be

somewhat decreased, but any spectral diffraction effect are likely to be completely avoided. At the dream of $1\text{J}/\text{cm}^2$, the size of the laser beam would not needed to be expanded before the compressor and decreased afterwards.

In case of the attosecond beamline, the dispersion management shall be first fixed. If gratings are needed, then the major efforts have to be devoted to achieve uniform and high efficiency over a bandwidth in excess of 300 nm.

Solutions – R&D directions:

Support research at industry towards high(er) damage threshold, broadband gratings, in co-operation with APOLLON, ELI-Beamlines, and ELI-NP. Separate R&D can be considered for development of high bandwidth ($>300\text{nm}$), high efficiency gratings even with a modest LTD of $0.1\text{J}/\text{cm}^2$. (Institute Fresnel, Jobin Yvon, SAGEM REOSC, Plymouth Grating Company, ...).

**I4. Large size ($\varnothing > 20\text{ cm}$) Ti:S crystal
(with FOM > 100 , appropriate homogeneity)**

There are small size Ti:S crystal available from several manufacturers with very high figure-of-merit (FOM) and excellent homogeneity. There are only a very few manufacturer, however, that producing laser grade Ti:S crystals at a diameter of 10 cm and above. The currently available largest diameter ($\varnothing \approx 17\text{cm}$) laser grade crystal is produced by Crystal Systems (in a joint R&D project with ILE). Promising research started at RSA le Rubin and Shanghai Institute of Ceramics.

Expected performance by the end of 2013, assuming the current trends and efforts:

$\varnothing \approx 20\text{ cm}$, FOM > 100

Evaluation:

By the time of the implementation of ELI-ALPS, it is likely that the technology of growing a Ti:S crystal with the necessary size and quality will be developed and available. Since the world-wide demand for such crystals is expected to be low, most probably the producing companies are needed to be supported to maintain the production line.

Solutions – R&D directions:

Some level of support for improving the quality and homogeneity of the Ti:S crystal is probably necessary, along with keeping the production line alive. (RSA Le Rubis, Crystal Systems).

5.3.2 Scientific R&D challenges

S1. Temporal contrast ($> 10^{12}$ on the target)

Currently the highest amplified spontaneous emission (ASE) temporal contrast of high power CPA laser systems is around 10^{10} , while it is 1-2 orders of magnitude better for relatively lower energy few cycle, OPCPA based systems. The so called short (ps) temporal contrast is poorer by several orders of magnitude for both cases. A 10 PW class laser would require, however, an ASE temporal contrast better than 10^{12} . The effect of post-pulses on the pre-pulse level is already discovered, but solutions are needed.

Expected performance by the end of 2013, assuming the current trends and efforts:

ASE contrast: $>10^{11}$, ps pedestal: $>10^8$, post-pulses are partially solved.

Evaluation:

It is very likely that the current and near future efforts in contrast enhancement and measurement technologies would result in an ASE and ps temporal contrast exceeding 10^{11} and 10^8 , respectively. In the case of short pulse pumped OPCPA systems, the ASE level is already satisfactory, while the short term (ps) contrast needs considerable improvement.

Solutions – R&D directions:

Dedicated R&D program is needed towards two main directions. One is for improvement of the sensitivity level of the measurement beyond 10^{14} , the other one is to clean the ps pedestal of the pulses. In addition, probably some more efforts are needed to solve the problem of post-pulses.

S2. Carrier envelope phase (CEP) stabilization (<50 mrad at 1kHz and lower)

Stabilization and precise control of the carrier envelope phase has been reliably solved for femtosecond oscillators, with an accuracy and noise better than 50 mrad at 8 fs pulses. With the use of a novel architecture, sub-30 mrad performance was demonstrated. There are commercially available systems also at kHz repetition rate and mJ energy level, but their precision is considerably lower than at MHz, moreover, their reliability has not reached the level of a facility-required operation yet. CEP stabilization at higher pulse energies than 10 mJ and considerably lower repetition rate than 1 kHz has not been accomplished yet.

Expected performance by the end of 2013, assuming the current trends and efforts:

CEP stabilisation: <20 mrad at MHz, <100 mrad at kHz.

Evaluation:

The demand for kHz repetition rate CEP stabilized systems may not increase substantially. So, industrial R&D is unlikely to be considerably further developed than the current level. At the high repetition rates (MHz and above), the demand is higher, cost is lower, so it is likely that the already high level of performance would be further increased.

Solutions – R&D directions:

Dedicated R&D program is needed for inventing novel, robust and reliable methods for CEP stabilization at kHz level, and even lower repetition rate.

5.4 Version 2: a 50 mJ / 10kHz, 1J / 1 kHz and 10 PW / 0.1 Hz triple laser chain

Upon the discussions held with the international user community, the primary inputs were to increase the repetition rate in the attosecond beamline, and also to make a reliable and robust system capable for operating as a real user facility right from the opening in early 2016. In order to meet the request of the community the laser scheme has been modified as compared to that of Version 1. The modified scheme is shown in Fig. 8 (identical with Fig. 1).

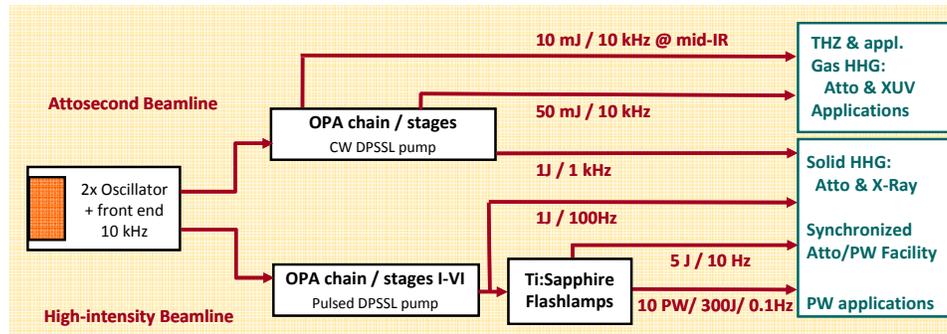


Figure 8. Current schematics of the laser systems of the ELI-ALPS Research Infrastructure with a list of secondary sources and applications (identical with Fig. 1).

The major changes are that now the repetition rate of the broad bandwidth, CEP stabilized pulses in the attosecond driver chain are expected to be kept initially at 10 kHz. In accordance to this, THz pulses are also generated at 10 kHz with the use of mid-IR pulses (Fig. 6), which are produced via difference frequency generation and / or as the idler wave of the optical parametric amplification stages. Partially due to the doubts on the available pump sources at 1 kHz (see above), the maximum output energy of the 1 kHz beamline has been reduced to 1 J. The generated pulses at both repetition rates are to be provided for HHG and attosecond generation and application in a user facility operation mode.

The high intensity beamline is changed only at one point: the 100 Hz mode would provide now 1 J energy pulses. The SHHG experiments are to be started with these pulses (Fig. 6). As soon as it becomes successful and robust enough, user access would be provided at 1 kHz repetition rate.

5.5 Major bottlenecks and possible solutions – version 2

5.5.1 Industrial bottlenecks

I5. kW class pump lasers at high repetition rate (6J @ 100Hz, 6J @ 1 kHz in IR, and 300 mJ @ 10 kHz in IR)

We start from the analysis given at 4.2.1 I1. The consequences are, however, different.

Expected performance by the end of 2013, assuming the current trends and efforts:

3 J @ 100Hz; 350mJ @ 1 kHz, 200mJ @ 10 kHz

Evaluation:

Regarding the specifications for 100 Hz and the 10 kHz pump lasers, the 1 J / 100 Hz and the 50 mJ @ 10 kHz specs are feasible.

The specs for 1 kHz are more relaxed than that in I1, but still difficult, as the prediction is 5× lower than the required single beam pump energy. The highlighted back-up solutions are more feasible now at this lower energy level, however, *efficient cooling of the Ti:S crystal* is still required at a level of 3 kW.

Solutions – R&D directions:

Pump laser development (Trumpf, Jenoptik, MBI, MPQ, ...)

Crystal head / cryogenic cooling development (Thales, ...)

The other three industrial bottlenecks are not affected by these changes, so **I2**, **I3** and **I4** are still held.

5.5.2 Scientific R&D challenges

The two challenges concerning temporal contrast **S1** and CEP stabilization issues **S2** are still held.

5.6 Version 3: a 2 mJ / 100kHz, 1J / 1 kHz and 3 PW / 10 Hz triple laser chain

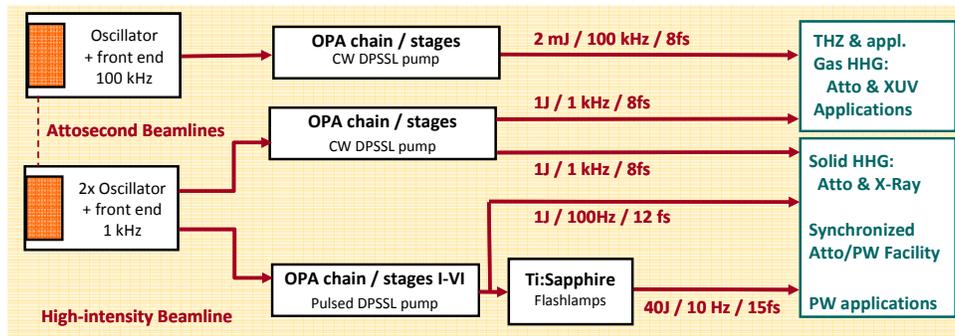


Figure 9. The “third generation” schematics of the laser systems of the ELI-ALPS Research Infrastructure. Synchronisation between the two types of front ends is possible – it depends on the wavelength range chosen for the 100kHz arm.

Having regarded all the bottlenecks and challenges above and also keeping in mind the uniqueness of the laser system based on repetition rate, a modified scheme is proposed (Fig. 9).

Here, a separate user facility channel would be devoted to low yield spectroscopy experiments as well as to GHHG generation at 100 kHz level, which we believe would attract not only fundamental physics but industrial R&D applications, as well. This system may be close in wavelength to the rest of the system, which may provide an obvious possibility of synchronisation to the other beamlines (as indicated by the dashed line in Fig. 9). However, it may also make sense to build this 100 kHz part operating in mid-IR. This is advantageous for producing HHG radiation with higher cutoff energy (scaling with the square of the wavelength) as well as for driving a high-average-power THz source. Although the possibility of synchronisation between the beamlines would be less obvious, the community may gain from the attractive light source at a different spectral range.

The concept of a dual laser system with common and synchronised front ends is still held on. There would be, however, two outputs of the kHz system. One is devoted for facility operations, while the other is for developmental and pilot experiments.

Concerning the high intensity branch, the separate 100Hz output would be still available at somewhat longer pulse durations, which can be devoted to ion acceleration experiments and related applications, too. The peak power of the highest intensity part is traded in for repetition rate. That is, now laser pulses at 3 PW level would be available but at 10Hz repetition rate.

5.7 Major bottlenecks and possible solutions – version 3

5.7.1 Industrial bottlenecks

I6. kW class pump lasers at high repetition rate (260J @ 10Hz, 6J @ 1 kHz in IR, and 10 mJ @ 100 kHz in IR)

There are flashlamp-based pump lasers available at 10 Hz repetition rate with a modest energy (15J). The ongoing developments in the field (especially BELLA at LBNL) would provide pump energy of 170J at a repetition rate of 5 Hz. Regarding 100 kHz lasers, there are currently available devices with pulses at mJ level. The analysis for the 1 kHz part given in I5 is still valid.

Expected performance by the end of 2013, assuming the current trends and efforts:

200 J @ 5 Hz; 350 mJ @ 1 kHz, 2 mJ @ 100 kHz

Evaluation:

The aimed specs for 10 Hz are certainly feasible. Cooling of the crystals at this repetition rate is getting a similar problem as highlighted above. The 1kHz part still needs to be considerably supported along with the 100 kHz branch.

Solutions – R&D directions:

Pump laser development (Continuum, Jenoptik, Thales, Trumpf, DESY, ICFO, MBI, MPQ, ...)

Crystal head / cryogenic cooling development (Thales, ...)

The next two industrial bottlenecks are not affected by these changes, so **I2** and **I3** are still valid.

The industrial bottleneck I4 does not play any role, as the size of the requested crystal is already available!

5.7.2 Scientific R&D challenges

The challenge of temporal contrast **SI** could be released by a factor of 5 at least, as the peak power of the pulses are lower.

S3. Carrier envelope phase (CEP) stabilization (<50 mrad at 100 kHz, 1 kHz and lower)

The CEP stabilization at 1 kHz is still challenging, but not more than described at S2. However, it becomes an issue for 100 kHz. The state of the art systems, based on fiber technology, exhibit a very poor stabilization performance of <0.5 rad, compared to the well established Ti:S technology. The 100 kHz systems working towards mid-IR, are, in principle, CEP stable.

Expected performance by the end of 2013, assuming the current trends and efforts:

CEP stabilisation: <200 mrad at 100 kHz.

Evaluation:

It is likely that some efforts are to be devoted by the scientific community to improve the CEP performance of the high rep rate systems. Due to the difficulties originating from the fiber amplification, a sudden huge improvement is unlikely.

Solutions – R&D directions:

A dedicated R&D program is needed for inventing novel, robust and reliable methods for CEP stabilization at 100 kHz level. In fact, it may also involves some developments in the laser chain itself. There are also some work to be done in the mid-IR concept based on OPCPA and DFG, as their performance has not fully established at higher energy level.

5.8 Version 4: a possible combination of the previous versions

Keeping in mind the above analysis, the scientific community is expected to make the final decision on the actual number of beamlines and repetition rates. Of course, the above schemes could be combined. A good and maybe very advantageous example would be Version 4 (Fig. 10), where the concept of Attosecond beamline was taken from Version 3 but with Version 2 parameters, while the High-intensity beamline from Version 3.

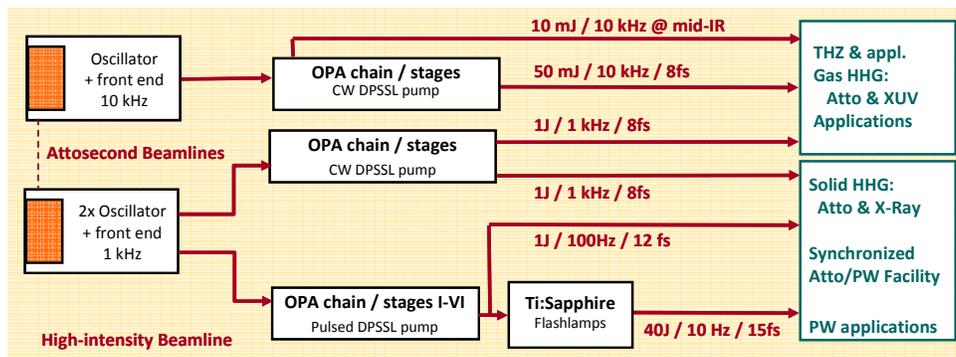


Figure 10. The “fourth generation” schematics of the laser systems of the ELI-ALPS Research Infrastructure.