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THRILL

TECHNOLOGY FOR HIGH-REPETITION-RATE
INTENSE LASER LABORATORIES

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About THRILL

The THRILL project deals with providing new schemes and devices for pushing forward the limits of research infrastructures (RI) of European relevance and ESFRI landmarks. To do so, the project partners have identified several technical bottlenecks in high-energy high-repetition-rate laser technology that prevent it from reaching the technical readiness level required to technically specify and build the needed devices, and guaranteeing sustainable and reliable operation of such laser beamlines at the partnering RIs. Advancing the technical readiness of these topics is strategically aligned with the long-term plans and evolution of the ESFRI landmarks FAIR, ELI (-BL) and Eu-XFEL, and RI APOLLON, bringing them to the next level of development and strengthening their leading position.

The project is focused and deliberately restricted to three enabling technologies, which require the most urgent efforts and timely attention by the community: high-energy high-repetition-rate amplification, high-energy beam transport and optical coating resilience for large optics. To reach our goals, the major activity within THRILL is organized around producing several prototypes demonstrating a high level of technical readiness. Our project is addressing not yet explored technical bottlenecks - such as transport over long distances of large-aperture laser beams via relay imaging using all-reflective optics - and aims at proposing concrete steps to increase the performances and effectiveness of the industrial community through the co-development of advanced technologies up to prototyping in operational environments.

The project is not only pushing technology, it is also offering an outstanding opportunity to train a qualified work force for RIs and industry. With this in mind, the structure of THRILL promotes synergetic work, fast transfer to industry and integrated research activities at the European level. Access to the RIs will be granted as in-kind contribution.

Executive summary

Getting towards the end of the THRILL project duration, we summarize our progress and findings in the topics of (i) actively cooled laser amplifiers for high-energy high-repetition-rate operation, (ii) beam transport and beam quality for high-energy laser systems, and (iii) large-area optical-coating capabilities. We discuss these results in terms of the envisaged system concepts of the next generation high-energy, high-repetition-rate (HEHRR) laser systems to be realized at Eu-XFEL and FAIR. In order to make sure that such infrastructures will be attractive for the end-user community, we have also reviewed the end-user needs and will summarize the main developments since the end-user workshop at the start of the THRILL project. We conclude that while several fields of research have evolved (e.g., laser-driven fusion or using HEHRR lasers in medical applications), the laser requirements continue to align well with the parameters that will be reachable, enabled by the progress in the THRILL project, in particular in terms of repetition rate.

Abbreviations

Abbreviation	Definition
HEHRR laser	high-energy, high-repetition-rate laser
LIDT	laser-induced damage threshold
ICF	inertial confinement fusion
IFE	inertial fusion energy
WDM	warm dense matter
QED	quantum electrodynamics

1 Introduction and objectives

During the THRILL project, technological developments have taken place in order to overcome the main bottlenecks for high-energy high-repetition-rate (HEHRR) lasers. Advances in actively-cooled high-energy laser amplification and alternative scaling methods, beam transport preserving good beam quality, and large aperture optical coatings with high LIDT (laser-induced damage threshold) have been achieved in this time distributed over the project partners. In this report we will summarize the output of the THRILL technical work packages and put them into perspective with the overall objectives of THRILL. In particluar, we will discuss how the new developments will enter the system designs of the future laser systems at the ESFRI landmarks Eu-XFEL and FAIR.

At the start of the THRILL project, we involved the end-user community to review the system parameters of high-energy lasers that are necessary to access physics questions in the field through state-of-the-art experiments. In the framework of a workshop in October 2023, discussions between the consortium and representatives of the end-user community took place, concluding that while THRILL cannot provide the next-generation laser technology for all fields of laser-matter interaction research, high energy (kJ-class), high repetition rate (shot/minute-scale), is sought after by a large part of the community. Fields of research that would benefit from such developments include:

- warm dense matter research
- dynamic compression of materials
- nuclear photonics
- inertial confinement fusion/inertial fusion energy
- magnetic field generation
- laboratory astrophysics

The conclusion was that end-user needs align well with the THRILL technical objectives.

When summarizing the output of the THRILL project, it is also important to review the current end-user prespective and relate to developments that have taken place since the time of the workshop. Chapter 2 of this report is devoted to this goal. Chapter 3, will present the technical advances achieved within the project and in Chapter 4, we will evaluate the findings in terms of system design.

2 System requirements for experiments

2.1 THRILL end-user workshop status-quo

	WDM/Comp.	QED/Nuclear	B- Field	Bio.	IFE	Lab Astro
Energy, pulse duration	kJ, ns (future ps)	0.1-1 kJ, fs	(several) kJ, (several) ns	1-100 J, fs	1-10 kJ, ns, ps	kJ, ns, (ps)
Rep Rate	NA but need more than single shot to generate high precision data	Yes, as high as possible	No	1-100 Hz	Ideally 10 Hz (1/min right now)	x100 increase compared to state of the art
Intensity (beam quality)	NA but intensity increase for future (higher pressure)	Very important parameter				
Peak Power	NA	Yes, as high as possible		0.1 – 1 PW		
Multibeam	Laser + XFEL	Optical-optical Optical-FEL	Makes sense in future in combination (three beams?)	no	yes	Optical-particle (proton, electron, x-ray)
Comment	Min. 100 J, kJ for precision, target limited			Stability and reproducibility		1/min can be sufficient for many years (ideally 1Hz)

Table 1: Summary of the laser-requirements for different research areas – status at end-user workshop 2023.

During the 2023 THRILL end-user workshop, the necessary laser requirements were discussed and are summarized in Table 1, which is taken from the workshop report[1]. There seem to be two fundamentally different laser parameter regimes that are interesting overall: kJ energy, long (ns) pulses and PW-class ultrashort (10s of fs) pulses. In terms if repetition rate there are also two different classes of applications: the ones that need Hz or higher operation and the other that would already benefit significantly if 1 shot/minute was available and would even be limited by targetry and detection to such repetition rates. Therefore, the overall conclusion was that while the THRILL project will not be able to provide all fields with the next generation laser technology, the direction set out

[1] https://www.thrill-project.eu/wp-content/uploads/2024/02/THRILL_D3.1_Report-on-end-user-workshop.pdf

for the project, i.e. high energy (kJ), high repetition rate (shot/minute), is sought after by a large part of the community. Development in this direction is fully justified by the end-user demands.

2.2 Recent developments

While in some of the research areas the user demands have remained unchanged since the end-user meeting, new developments have also taken place. Here we will review the implications of these on the end-user requirements.

Since the beginning of the THRILL project, research on **inertial confinement fusion (ICF) / inertial fusion energy (IFE)** gained significant momentum largely due to the repeated demonstration of ignition at the National Ignition Facility (NIF) in the USA since 2022, with ever increasing gain, currently reaching > 4. This development fuelled societal interest and resulted in newly established national funding programmes (across Europe mainly in France, Germany and the UK). While these programmes are mostly pursued by industrial actors, a growing role is also taken up by the HEHRR facilities represented in THRILL, as an inherent part of the upcoming fusion ecosystem.

Recent research activities have yielded new findings, which have highlighted that in addition to efficient pumping, kJ-class laser pulse energy and the high repetition rate (on the order of 10 Hz), which are necessary for IFE, fundamentals of the laser-matter interaction also impose requirements on the driver lasers. Broadband nanosecond pulses with low temporal coherence appear to be the most promising way within the compression-based (central-hotspot and direct-drive/indirect drive) approaches to mitigate laser-plasma instabilities and therefore allow for optimized energy coupling from the driver laser into the fusion target. Developing the frontend technology and frequency conversion schemes for such pulses, has not been part of THRILL, but the consortium has now recognized this as a new challenge for the community, thereby identifying a necessary future development direction.

A distinct, complementary development since the workshop, is a renewed focus on short-pulse-driven fast ignition. Here, compression and ignition are decoupled: ultra-short, high-intensity pulses heat the pre-compressed fuel directly on picosecond timescales, relaxing the compression requirements and introducing a short-pulse ignition driver as a laser category in its own right alongside the ns compression driver. As a consequence, in addition to the requirements listed in Table 1, research in this direction requires multi-beam capabilities of the research infrastructure, where a short-pulse high-intensity beam and one or more long-pulse high energy beams can be used in combination.

In the fields of **warm dense matter research, dynamic compression of materials, magnetic field generation**, and **laboratory astrophysics,** laser requirements have remained mostly the same as presented in Table 1, but progress on the current challenges has also been made. An increase of repetition rate from few shots per day to few shots per hour would already allow for systematic scans and therefore extend the scope of such experiments significantly. In order to maximize the impact of these new technologies, users must shift how they deploy targetry for these types of experiments, as currently the complex target structure limits the experiment feasibility. Recent, proof-of-principle experiments have been developed at even higher repetition rates (1 Hz) using e.g., the DiPOLE

laser for photon-hungry spectroscopy experiments at Eu-XFEL[2], that allowed first experiences with the challenges involved, such as debris generation and shielding, reproducible sample quality and alignment, automated beam alignment, and high-speed data acquisition. These challenges represent the next bottlenecks for future experiments, once the HEHRR laser systems are routinely operational. While the study mentioned above and others[3] represent first attempts, systematic development is necessary which has not been covered in the THRILL project, but has now been identified as such by the consortium.

For research in **high-field QED** and **nuclear photonics** the laser requirements remain also mostly unchanged, in that the peak intensity and repetition rate determine the feasibility of observing a certain process. With current laser facilities, already very low signals can be made detectable, by applying special techniques, such as dark-field detection for vacuum birefringence[4]. As rep-rated high-power lasers become increasingly available, focused intensities should target to exceed 10^{23} W/cm^2 which is not yet available, but would allow for exploiting the RPA ion acceleration mechanism in nuclear photonics with several advantages over the still dominating TNSA scheme, provided that the temporal contrast can be kept sufficiently high. However, even more importantly, the high repetition rate laser at highest peak powers can only be applied to their full potential, if automated stabilization and control ensures optimized performance with stable and reproducible parameters. Integrated laser/targetry systems are also crucial in this respect. These requirements, in addition to online diagnostics, capable of high repetition rate data taking, align well with those of the research areas mentioned above and represent upcoming challenges. Despite these ongoing and future developments, significant progress in the field, in particular in the astrophysical context, is expected in the near future, as a number of facilities are approaching a state of productive user operation, beyond test and commissioning experiments (e.g. ELI).

While in the field of **medical applications** the main focus has been on using the secondary sources of particles and radiation for diagnostic imaging and therapy, one newly emerging application is the laser-assisted production of radio-isotopes. In the context of research infrastructures, the development of high-energy high-repetition-rate lasers can have significant impact. While there exist two traditional ways to produce radio-isotopes using nuclear reactors and/or standard particle accelerators, the field suffers from four main issues: first, there is a growing demand for cancer treatment and diagnostics, in particular for established radio-isotope pairs used for the simultaneous treatment and imaging (theranostics). Second, the demand for new isotopes is very high in biological research. Third, the decommissioning of available reactors worldwide reduces the world production of certain established radio-isotopes produced as by-products from research reactors. Finally, compact accelerators are usually optimized for the production of a single species and do not offer the versatility required in research.
To support research in theranostics and other methods exploiting radio-isotopes, lasers could offer an attractive solution since a single laser facility can produce various sorts of secondary radiations from x-rays, to protons, electrons and neutrons, through a choice of the interaction target. This versatility has been recognized and is currently being explored within the EUROPA project for

[2] D. Kraus, private communication (2026)
[3] M. D. Balcazar et al., Nature Communications **17**, 529 (2026)
[4] M. Šmíd et al., Phys. Rev. A **112**, 063512 (2025)

instance[5], or in connection with ELI-NP[6]. An essential goal here is the production of new radio-isotopes at the megabecquerel level per sample, which enables their purification, their vectorization (attachment to a biological molecule) and study in small-animal models.
Given the current understanding of the conversion process from laser light into radio-isotopes, it is established that ultrashort pulsed lasers reaching the relativistic laser-matter interaction regime and with peak powers in the range 0.1-1 PW are ideally suited. However, the yield of production of radio-isotopes is not very high and the goal in terms of sample activity can only be reached by increasing the average power – i.e., the repetition rate of the laser. To this end, similar to the requirements in nuclear photonics and high-field QED, automated stabilization and control is needed for optimized performance, as well as debris management, which becomes a challenge at the high repetition rates.

In summary, the demand for radio-isotope production for medical research purpose, while it has not been considered earlier in the end-user requirement review at the beginning of THRILL, translates into laser requirements, which align well with the requirements described in Table 1 for the other medical application. Just note that the requirements here are at the higher end of the range initially given, underlining that research on radio-isotope production is probably one of the most demanding applications in terms of expected laser performance.

3 THRILL technical advances

3.1 High-energy high-repetition rate amplification

The main limiting factor in the operation of kJ-class, flashlamp-pumped high energy lasers is the thermal load on the amplifier modules (amplification medium as well as the entire module), which leads to distorted wavefronts and thereby a risk to the amplifier and the optical components of the laser chain due to the impact on the energy distribution in the laser beam. Typical repetition rates in systems that are not actively cooled are in the few-shots per day range. In order to increase this rate, active cooling is necessary. Several approaches, based on liquid and gas cooling, have been investigated within the THRILL project. We will summarize the findings acquired during the work on the different approaches in this chapter and detail their respective impact on the upcoming laser system designs in chapter 4.

3.1.1 ATON

The ATON system at the L4 laser at ELI-Beamlines operates a Nd:glass amplifier system, pumped by flashlamps, fully immersed in a cooling liquid, in order to reduce the thermally-induced distortions of the wavefront. Extensive characterization of the ATON system took place within THRILL, which can be found in detail in task report[7].

[5] https://europa-project.eu/
[6] Dr. LASER: https://www.eli-np.ro/thematics/drlaser.php
[7] https://www.thrill-project.eu/wp-content/uploads/2024/08/D4.1-Report-on-the-characterization-of-ATON-laser-amplifier.pdf

Demonstrated parameters and features of the approach

- actively (liquid flow) cooled amplification in Nd:glass slab amplifier modules with apertures of 18 cm and 30 cm, depending on the different stages (corresponding to beam diameters of 14 cm and 23 cm, respectively)
- repetition rate up to 1 shot per minute was demonstrated
- active cooling allows for an increased repetition rate by a factor of at least 10 compared to passive cooling (i.e. no flow of the cooling liquid)
- amplification of CPA pulses (stretched duration 3 ns, compressible to 150 fs), or long-pulse mode (nanosecond pulses of 1-10 ns duration with amplitude shaping)

Further scalability and limitations

- The repetition rate is limited to 1 shot per minute, which is achieved in a thermal steady-state. However, it is necessary to actively control the pressure of the coolant and perform dynamic wavefront corrections to reduce wavefront aberrations and achieve a good focus quality.
- Scalability in terms for pulse energy depends on maintaining these coolant pressure requirements, the wavefront control and the availability of the respective Nd:glass material in larger apertures. An operating fluence of ~3 J/cm^2 is feasible.

3.1.2 PAMDAM

The liquid-cooled Pseudo Active Mirror Disk Amplifier Module (PAMDAM) concept for large aperture Nd:glass amplifiers, has been developed and applied at Amplitude for several years. Within THRILL, the scalability of such a module from 100 mm aperture to 200 mm aperture was investigated, in order to evaluate the feasibility of using PAMDAM modules as building blocks for kJ-class lasers at high repetition rate. A detailed description of the work done and the results can be found in the PAMDAM task report[8].

Demonstrated parameters and features of the approach

- Ø200 mm PAMDAM amplifier module allowed for the amplification of Ø170 mm pulses in flash-lamp-pumped Nd:glass (Schott LG760) discs at a repetition rate of 1 shot / 20 sec, relying on existing and affordable technology.
- highest repetition rate achieved within the approaches investigated in THRILL
- steady-state wavefront reached after ~10 min
- long-term operation reliability was tested over more than 1 year
- Different and novel cooling fluids were tested because it is well known that water causes Nd:glass degradation. Their limitations were analyzed, leading to the conclusion that the use of fluorocarbon or organic solvent is limited by the degradation of the cooling fluid itself.
- a transmission of 96.5% was measured when using an index-matched cooling fluid
- a small-signal gain of 0.3 was measured using water, amounting to ~300 J of stored energy corresponding to ~160 J of available laser energy, which, owing to the special active-mirror-like

[8] https://www.thrill-project.eu/wp-content/uploads/2025/07/THRILL_WP4.2_PAMDAM-Characterization-Plan.pdf

geometry, is 50% higher than that measured in similar large-disk amplifiers of the same material
- patent application was filed for pumping scheme (FR2601482)
- PAMDAM concept allows for the laser propagation, the pumping and the cooling gradient to be parallel, at 0° AOI, limiting thermal aberrations.
- The PAMDAM split-disk concept spreads the thermal load more evenly and increases the surface available for thermal extraction, enabling large increase in repetition rate.

Further scalability and limitations
- 6 PAMDAM amplifier units could reach 1 kJ-scale pulse energy at 1053 nm at 1 shot / 10 s
- The proximity of flashlamps causes large transient flashlamp shock on the amplifier medium, which induces significant wavefront aberrations. For operation with high beam quality, re-engineering of the flashlamp coupling is needed.
- remaining challenge: adhesion of ASE absorbing cladding in fluorocarbon cooling environment

3.1.3 GSI module

The third approach, carried out by GSI on the PHELIX system, aims at upgrading the existing 315-mm-aperture amplifier modules with liquid cooling of the flashlamps and housing, as well as active cooling for the amplifier medium itself (gas or liquid). Keeping the main features (size, flashlamp array design, pulsed power units) of the original amplifier heads, comes with the advantage, that the new developments can be tested in a real operational environment without any additional space and infrastructure requirement, or more device development. To date, the actively liquid-cooled flashlamps in combination with the passively cooled Nd:glass slabs have been tested, showing a dramatic reduction of the cool-down time constant of the amplifier module to 3 minutes.

Demonstrated parameters and features of the approach
- amplification of 280-mm-aperture beams in Nd:glass disks has been shown at a repetition rate of 1 shot / 30 min to the few-100 J level (at 1053 +/- 5 nm), relying on existing and affordable technology
- amplification of CPA pulses (stretched duration 3 ns, compressible to ~0.5 ps), or long-pulse mode (nanosecond pulses of 1-8 ns duration with amplitude shaping), or incoherent broadband ns pulses
- test in operational environment

Further scalability and limitations
- operational fluence of 3.5 J/cm^2 would lead to an upper limit of 5.5 kJ pulse energy in a beam of 40 cm x 40 cm, further scaling depends on the availability of large-size laser glass slabs, which is not certain
- repetition rate expected to be increased to 1 shot / 10 min by further optimization of the flash-lamp cooling design (verification pending still within THRILL)
- beyond this, the repetition rate is limited by the passive cooling of glass slabs

3.1.4 Coherent beam combining

As an alternative approach of increasing the pulse energy, coherent beam combining was also investigated. Here, operational amplifier geometries are multiplexed to keep amplifier characteristics, such as the repetition rate and the beam quality the same, but lead to an increase in achievable pulse energy. The multiplexing can be carried out both in a passive or an active way, both routes are being explored within THRILL.

Demonstrated parameters and features of the approach

- demonstration of passive coherent beam combining with a 45-mm-diameter beam at a repetition rate of one shot every 20 minutes
- energies in the range of several 10's of Joules have been shown, which would not have been possible in a single amplifier due to gain saturation and B-integral
- feasibility of active beam combining has also been shown, by the measurement of the phase between two independent flashlamp-pumped beams, allowing for compensation

Further scalability and limitations

- scaling necessitates increased number of laser systems (passive) or amplifier arms (active), leading to increased complexity of the system, in particular when scaling to kJ is considered

3.2 Beam quality and transport

In addition to high repetition rate laser amplification, preserving and actively correcting the wavefront, as well as beam quality-preserving transport is essential to provide reproducibly the highest intensities on target for the applications. To this end, THRILL has allowed progress in real-time wavefront correction for which software integration represents an important aspect, and a design and alignment procedure for an all-reflective transport telescope, adaptable to the various laser installations of the THRILL partners.

3.2.1 Real-time adaptive optics

In order to ensure reproducible shot-to-shot parameters in a high-energy laser, fluctuations in the system have to be either controlled or corrected for. Typically, such fluctuations (due to air movement or turbulences and other environmental effects) occur on a much faster time scale than the shot rate in HEHRR systems, even when operated at a repetition rate of 1 shot per minute or up to 1 Hz, which are very high repetition rates for such lasers. Still the shot-rate is not high enough for shot-to-shot correlations and corrections. Therefore, in THRILL a method has been developed to overcome this limitation and apply real-time corrections to the wavefront by monitoring the wavefront evolution in real time and also enabling real-time corrections with a deformable mirror.

Demonstrated scheme and features of the approach

- off-spectral CW pilot beam for system-state-agnostic beam quality monitoring, implemented at Apollon
- high-speed, real-time wavefront sensing with up to 7 kfps, which allows for full monitoring and characterization of dynamic aberrations over relevant time scales
- adaptive optics code is fully open source
- real-time adaptive optics control in a pre-compensation configuration, granting a stability of

< 1% rms fluctuations in the Strehl ratio, as demonstrated at Apollon

Further scalability and limitations

- deterministic optimization of delivered beam characteristics enabled
- adaptive optics: transferable to other large-scale laser facilities and horizontally scalable
- however, high-quality relay imaging throughout the system is a precondition
- the pre-compensation approach makes the loop susceptible for control matrix degradation, such as misregistration, leading to erroneous corrections
- machine safety concerns not yet fully addressed – on-shot demonstration is still pending
- high complexity, especially the software, with the risk of knowledge concentration

3.2.2 Software architecture for adaptive optics integration

To tackle the challenge of integrating the complex adaptive optics controls and other control elements into a laser-control software framework as universal and open as possible, a prototype software architecture for textfile-configurated integration of AO/control components was developed. The modular approach is based on ZeroMQ inter-process communication.

Demonstrated scheme and features of the approach

- the underlying software architecture allows for integrating adaptive optics, diagnostics, and active beam-control components into facility control systems
- textfile configuration makes logic explicit and configurable without hard-coding the full control topology
- nested workflows and tunnels allow complex AO/control schemes to be composed from smaller reusable building blocks
- stronger software structure for longevity
- open-source Python-based prototype encourages community participation

Further scalability and limitations

- scalable from simple demonstrators to distributed multi-process control setups
- reusability due to separation of hardware-specific device tasks from workflow-level control logic
- lower integration effort for AO in facility environments
- currently still a prototype/demonstrator and not yet validated in full AO operation
- real-time performance is not inherent to the structure and may require separate handling
- interfaces to commercial hardware may be protected IP

3.2.3 All-reflective relay image telescope design

In large-scale laser facilities, where beam sizes exceed tens of centimetres, the large number of interfaces with mid-frequency wavefront imperfections and the long propagation distances necessitate the use of relay-imaging beam transport. This ensures beam quality and minimizes modulations to the lowest possible level. More particularly, in the context of ultra-high-intensity lasers, such as the Apollon laser, the use of reflective optics (spherical or off-axis parabolic mirrors) is necessary to construct these relay-imaging telescopes to avoid chromatic effects and reduce the accumulation of non-linearities, especially in the final stages of the laser chain. Within the framework of the THRILL project, the Apollon team designed and scheduled the integration of a new telescope

based on small off-axis angle parabolas between the last amplification section and the 1 PW beamline compressor. This setup saves about 20 meters of free beam propagation and improves the beam fluence distribution, particularly on the compressor's final grating.

Demonstrated scheme and features of the approach

- relay-imaging telescopes based on reflective optics built in Apollon facility, using off-axis parabolas
- fully achromatic imaging, no additional B-Integral, no contrast degradation, which is particularly important in broadband, short-pulse, and ultra-high intensity systems to bridge long propagation distances

Further scalability and limitations

- design to be transferred to other THRILL partners (EU-XFEL, FAIR) with adapted alignment procedure
- alignment challenging: the use of specific equipment and procedures is necessary, because the alignment of off-axis parabolas is more challenging than in lens-based telescopes, especially during commissioning
- sourcing of high-quality, large-aperture off-axis parabolas is critical to achieving good performance

3.3 Large aperture optics

3.3.1 Large area coatings

At ELI Beamlines, the ELIAS large-area coating chamber was commissioned as part of the THRILL project. With this infrastructure, large optics up to 1.2 m in diameter will be available for the academic community in Europe, thereby supporting HEHRR systems with some of the most critical components.

Demonstrated scheme and features of the approach

- Several types of large area coatings have already been developed and demonstrated using ELIAS, which is based on electron beam evaporation technology:
  a) Gold mirrors have been coated on 1045 x 710 mm size substrates. Spectral performance was uniform over the whole area. Coated components have been used to transport 5 PW power pulses (154 fs and 786 J) without any damage.
  b) Dichroic antireflection coatings (AR<0.1 %@ 527+1030 AOI=0 deg) have also been coated on 0.5 m size optics. It is currently in use with ns, pulsed, >1 kJ beams and no damage was observed. Coating consists of four HfO_2/SiO_2 layers. Spectral uniformity has been measured to be < 0.5 %.
  c) High-reflection multilayer dielectric coating (HRp>99.7 %@ 1040-1080 AOI=45 deg) was deposited on 250 x 350 mm size substrate. Pulses of 1-2 ns duration and >1 kJ were used during user campaign and no damage was observed. Test sample with lower reflectivity was tested in HiLASE using 8.4 ns pulses and 213 µm spot size. Evaluated LIDT value was 84.8 J/cm^2. Measured spectral uniformity over one meter diameter was <1 %. Additionally,

flatness was measured on witness sample. Measurements showed the change in power value from 0.133λ to 0.118λ, indicating very low stress values.

- Due to inherent porosity of deposited coatings, optical components have very high laser induced damage threshold in ns regime. E-beam deposition is also very flexible and can be used to coat oxides, metals and fluorides without large modifications or safety issues.
- The demonstrated developments show the capabilities to coat optical components for multi-kJ energies and multi-PW laser facilities. It was demonstrated that ELIAS is capable to coat 1.2 m size optics with <1 % uniformity, which can be improved to the level of <0.2 % by fine tuning the setup. Ultrafast metal mirrors of 1.2 m demonstrated higher damage threshold than expected and seem to enable 10 PW peak power at 150 fs and potentially more with shorter pulses. This is critical mainly for short focal length final focusing OAPs, which require a chemically removable coating.
- >1 m scale, high LIDT, ultrafast MLD optics enables rep-rated operation of new facilities with very high efficiency.

Further scalability and limitations

- Given the uniformity, very sensitive optical coatings can be produced as well like i.e. large polarizers or diffraction gratings.
- The LIDT values achieved on samples and validated in operating conditions gives very important feedback to the amplifier design. This is mostly relevant in the regime of about a shot per minute region, which is mostly unexplored in the kJ regime.
- scaling of e-beam coating to the optic size of two meters possible
- The main e-beam coating's possible disadvantage is spectral shift caused mainly due to porous thin films absorbing humidity. Such effect can be suppressed by densifying coatings with a plasma source. However, this approach for meter scale optics requires extensive development time.

3.3.2 Conducting ITO coating

Conductive antireflection coatings with a buried Indium Tin Oxide (ITO) layer are a promising path towards large aperture Pockels Cells without the need to form complex conductive plasma electrodes around the crystal. The feasibility of such coatings, as well as the LIDT of these special coatings has been explored within THRILL in order to open a path towards large Pockels cells based on DKDP crystals.

Demonstrated scheme and features of the approach

- design and test on fused silica samples
- coating on KDP crystal, including electrical contacts
- full Pockels-Cell produced and tested
- LIDT for all main designs (800 nm and 1064 nm) at several facilities (HZDR, FTMC and ELI)
- LIDT values reached ~13 J/cm^2 at 800nm (0.25 ns) and 6.85 J/cm^{2}at 1030 nm (2 ns)
- Demonstrated developments show the approach can be integrated into high-energy laser systems as the LIDT of the conductive coating is no longer the bottleneck of the design.
- The main use will be found in back reflection isolation for high-energy lasers such as those planned for Eu-XFEL and FAIR projects.

Further scalability and limitations

- approach scalable to 500 mm apertures thanks to the IBS coating process
- Rise time requirements have to be balanced with the LIDT levels needed, as one goes against the other. This is mainly relevant for “regenerative type amplification” needing fast switching.

4 System-design considerations

The development work described in chapter 3 immediately leads to design considerations that will benefit the next generation HEHRR laser facility to be built at the sites of FAIR (Darmstadt) and Eu-XFEL (Schenefeld) in Germany. Both installations will address the end-user needs for various aspects of the research fields described in chapter 2, that complement each other. The added value of their unique location is their vicinity to a large-scale facility. In the case of FAIR, the HEHRR laser system will be on the campus of the newly built heavy-ion accelerator facility, where the laser pulses can be used in combination with the high intensity heavy ions. At the Eu-XFEL, the free-electron-laser facility provides an X-ray source for precision diagnostics of processes induced by the HEHRR lasers. Both facilities have previous experience with building and operating high-energy lasers, i.e with PHELIX at GSI, and ReLaX and DiPOLE of the HiBEF instrument at the Eu-XFEL.

The design considerations described in this chapter are based on the current state of development and technical readiness levels. Their feasibility is also subject to the availability of special, large-size optical components, some of which can currently only be sourced from outside Europe, imposing an inherent risk. While coherent beam combining is currently at a lower TRL, it is not affected to the same extent by this sourcing risk. Further development of this direction is therefore essential as a longer-term risk-mitigation strategy.

4.1 Future laser system at FAIR

With the upcoming FAIR facility in Darmstadt, unprecedented high intensity beams of heavy ions will become available. In order to provide optimal tools for the research fields described in chapter 2, a new laser facility is necessary in the vicinity of the APPA cave, which will house the plasma physics experiment station at FAIR (cf. Figure 1). The artist’s impression of the building feasibility study is shown in the inset. The laser system envisaged here has been named SIRIUS (**S**c**I**entific **R**esearch **I**nfrastructure for **U**niversal laser-plasma **S**tudies), and targets the following laser parameters:

- multi-beam facility (4 beams with several kJ pulse energy each)
- architecture allowing for several types of frontends to enable ns, ps, fs, and incoherent broadband option (1.5% bandwidth)
- repetition rate 1 shot /10 minutes

The choice of the facility objectives represents the current state of development and technology readiness. With the progress within THRILL, the realizability of such a facility in the mid-term future (5-7 years) appears feasible. Naturally, adjustments in parameters and possibly conceptual aspects might become necessary, depending on future development outcomes.

The SIRIUS laser system will comprise several laser amplifier chains, each consisting of the parts below, for which we have highlighted the THRILL developments in the design choice:

- Frontend – pulse generation and shaping, providing the input for the different output options (ns, ps, fs, and incoherent broadband), mJ level output
- Pre-Amplifier – based on proven PHELIX technology using flashlamp-pumped rod amplifiers, that are already in operation, mJ-level to few joules of output energy
- **Main Amplifier –** increases the pulse energy from the joule level to energies exceeding (few) kJ for each beamline at 1ω. Proven PHELIX technologies will be adapted throughout, with the addition of the THRILL actively (water) cooled amplifier modules in the PHELIX design to allow for the repetition rate. Two-stage amplification is envisaged: double-pass amplification in mixed-glass modules with staged beam expansion and large-aperture optical isolation, followed by single-pass, mixed-glass booster amplifiers.
- Beam conditioning and **transport –** In terms of beam conditioning (pulse compressor for fs pulses and second harmonic generation for the narrowband and broadband ns pulses), the existing solutions operational at PHELIX will be scaled to the necessary apertures. In order to preserve beam quality and throughput before coupling into the experiment, reflective transport optics are used for short pulses to limit nonlinear phase accumulation, while long-pulse transport employs long-focal-length transmissive optics. The design developed within THRILL will give an excellent starting point.
- Control system and timing – essential for safe, reliable, and efficient operation, will be upgraded for high repetition rate operation
- **Beam control** and beam diagnostics - Beam quality and stability are critical for reproducible focal spot performance. An integrated adaptive optics system to stabilize the beam throughout the amplifier chain and optimize the focal spot at the target will be implemented based on the THRILL developments described in chapter 3. A cascaded architecture combining wavefront correction and pointing stabilization is realized using deformable mirrors, sensors, and a pilot-beam infrastructure. Beam diagnostics are an essential part of monitoring and stabilizing the system.

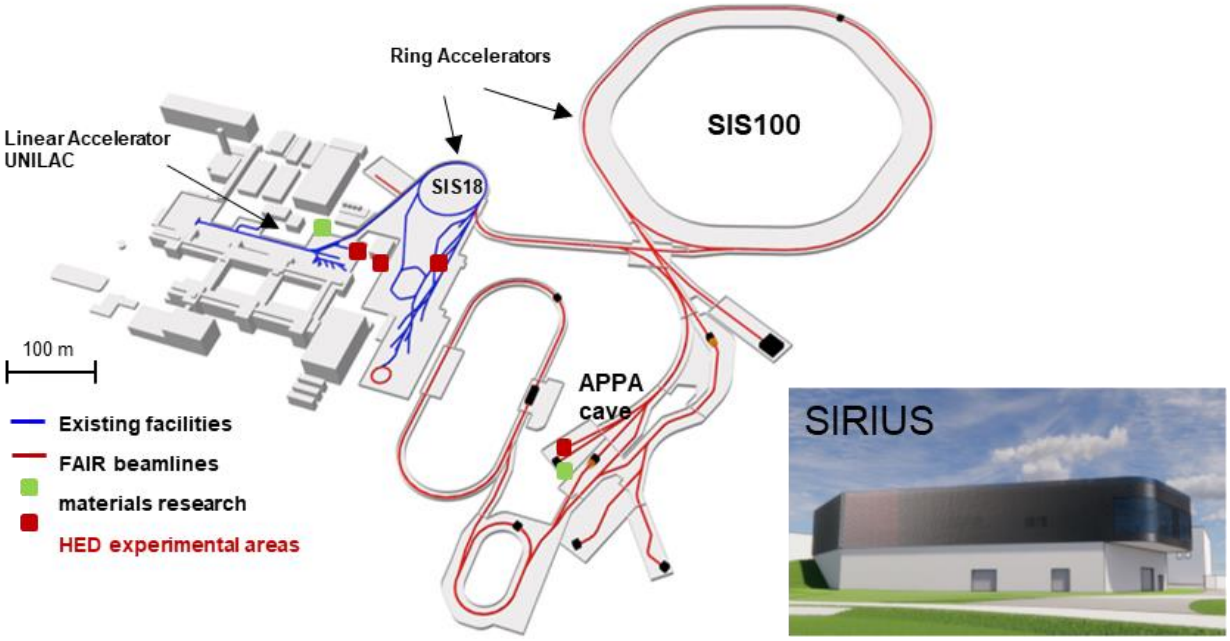


Figure 1 Layout of the FAIR facility with the envisaged SIRIUS building (shown in the inset) next to the APPA cave

4.2 Future laser system at Eu-XFEL

The laser design envisaged for the Eu-XFEL is a modular high-energy Nd:glass laser system, employing a mixed-glass amplifier architecture. It is designed to provide both kilojoule-class long pulses and petawatt-class short pulses, while being fully integrated into the Eu-XFEL infrastructure and allowing for future expansion through additional beamlines and amplifier stages. The design concept was summarized by Sinn et al.[9]. The multi-beam laser system will be housed in a dedicated laser hall in the **SASE4** area, while the experiments will be carried out in two target chambers located in the **XTD8 tunnel**, as can be seen in Figure 2

The main features of the laser design are:

- Repetition rate of 1shot per 5 minutes, at kJ energy level, using water-cooled flash-lamp-pumped technology as investigated in THRILL. At lower energy levels, even higher repetition rates are achieved by diode-pumped technology.
- Synchronization of fs laser with the X-ray pulses is crucial for precision experiments. Based on experience with the present laser installation, synchronization and continuous pulse arrival monitoring to sub-30 fs will be achieved.
- Full integration into Eu-XFEL control system Karabo including highly automized control and online-analysis functionality, which has been developed within the THRILL project and tested with the Dipole 100-X laser system.

[9] https://xfel.tind.io/record/4410?v=pdf

- OPCPA-based preamplifier technologies allowing for > 20 nm bandwidth for both broad-band long pulse and sub-150-fs CPA pulse generation.
- For preserving beam quality during transport, all-reflective telescopes developed in THRILL will give a starting point for dedicated beam transport lines, which are compatible with both short-pulse and broadband long-pulse operation

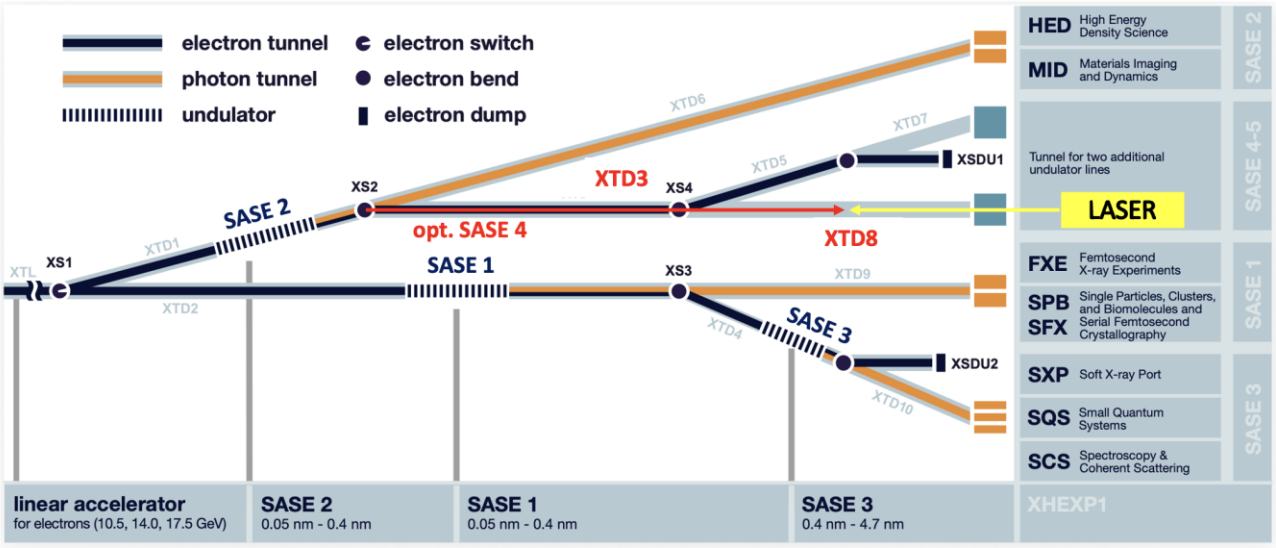


Figure 2 Overview of the Eu-XFEL experiment facility, showing the location of the envisaged laser system and the experiment area.

5 Conclusions

The technical developments in the THRILL project have contributed noticeably to the maturing of the HEHRR laser technology, covering the different challenges in this field. The main bottlenecks, that were identified as the focus of the THRILL project, are the actively cooled Nd:glass-amplifier technology, the wavefront correction and preservation during transport of high-energy, large-aperture beams, and the sourcing of large size, special optical components. In this report we have summarized the different paths, that we have explored, and have shown how our findings have entered the design considerations for the next generation of HEHRR lasers in connection with the Eu-XFEL and the FAIR facility.

The main points are summarized below

- While the research fields served by HEHRR laser systems have evolved since the start of the THRILL project, the overall laser requirements of the **end users** have not changed significantly. A repetition rate of one shot per few minutes remains an attractive goal for the majority of applications, which already brings along the challenge and necessity of novel ways to design and deploy targetry in such experiments. For the renewed interest in laser-driven fusion, incoherent broadband pulses have become additionally relevant, as well as multi-beam requirements with the possibility of a combination of a short-pulse PW option and one (or more) ns-scale kJ-class beam.

- For the **SIRIUS** laser infrastructure at **FAIR**, the actively cooled amplifier heads in the PHELIX-geometry are envisaged to reach (few) kJ pulse energy at 1 shot/10 min repetition rate. Beam quality and transport will also build on the THRILL developments and results.
- The **Eu-XFEL** system aims for kJ-class laser pulses at 1 shot / 5 min, which are synchronized to the X-ray pulses of the XFEL. The active water cooling of the amplifiers, beam transport and beam quality, as well as integration into the accelerator control system, will be based on the achievements in THRILL.

On the path towards the realization of these two new HEHRR laser infrastructures in the mid-term future, the main risk has been identified to be the sourcing of large special optical components, which in some cases is currently only possible from outside Europe. While the consortium has become aware of this risk and is undertaking steps towards its mitigation, the recommendation is to continue to investigate and develop the path of coherent beam combining as an alternative route towards kJ-class high repetition-rate lasers. This way the technical readiness level will be available should a change in design considerations become necessary.