THRILL

TECHNOLOGY FOR HIGH-REPETITION-RATE
INTENSE LASER LABORATORIES

Deliverable Data	
Deliverable number	D3.1
Deliverable name	Report on end-user workshop
Work Package	WP3
Lead WP/deliverable beneficiary	GSI
Type and dissemination level	Report, public
Deliverable status	
Submitting author	V. Bagnoud, Zs. Major
Verified (WP leader)	Zs. Major, D. Kraus (end-user board)
Approved (Coordinator)	V. Bagnoud
Due date of deliverable	31.12.2023

Funded by
the European Union

This project has received funding by the European Union’s HORIZON-INFRA-2022-TECH-01 call under grant agreement number 101095207

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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 will be organized around producing several prototypes demonstrating a high level of technical readiness. Our proposal 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

The THRILL project aims at federating the international community around the topics of high-energy laser for large research infrastructures. For this, it is essential to establish a dialogue between scientists and users of such facilities and laser developers, in order to manage the expectations of the former and guide the effort of the latter.

The workshop held in Ingelheim, Germany, brought together researchers representing the many fields of research involved in exploiting these facilities. The topic was the definition of the parameters for the next generation of high-energy high-repetition-rate lasers, the technology that is at the center of the development work in THRILL. The contributions of the invited speakers and the following discussions outlined the main requirements of the end-users for future laser systems. While some of the parameters were spread over a wide range, a consensus emerged that kJ-class, long pulse (ns) lasers at a repetition rate of 1 shot/few minutes would allow to access a wide range of new physics questions and represent a “game changing” development for many research fields. In addition, the need for shorter pulses in the femto- and picosecond range remains unchallenged, either to drive QED experiments or for secondary radiation source generation, with an emphasis on laser beam quality and high-fidelity amplification.

These findings are very well aligned with the envisaged development directions of the THRILL project.

1 Introduction and objectives

1.1 Objectives and participants

The end-user workshop had the goal to provide an overview of currently pursued research directions using high-energy lasers, in particular in combination with large-scale facilities. Researchers in the relevant fields were asked to present what physics questions can be accessed in their respective fields by using high-energy lasers. They were also asked to discuss limitations imposed by the presently available laser systems and what laser parameters would be desirable for the future. The overall objective of the workshop was to obtain input from the end-user side towards the specifications for the next generation of high-energy lasers to be developed for research in combination with EuXFEL and FAIR, the conceptual design of which is the overall goal of the THRILL project.

The table below shows the topics covered, the invited speakers, and their respective institutions or facilities.

Topic of contribution: HEHRR laser requirements for	**Speaker**
WDM research	Tommaso Vinci (LULI)
	Dominik Kraus (University of Rostock)
Nuclear Photonics	Ovidiu TEȘILEANU (ELI-NP)
	Peter Thirolf (LMU Munich)
dynamic compression of materials	Andrew Higginbotham (University of York)
Inertial Fusion Energy	Florian Wasser (Focused Energy)
	Laurent Masse (LULI)
magnetic field generation	Joao Santos (CELIA)
	Nigel Woolsey (University of York)
high-field QED	Matt Zepf (Jena University)
	Eva Los (Imperial College)
Laboratory Astrophysics	Frederico Fiuza (SLAC/IST)
	Carolyn Kuranz (University of Michigan)
societal aspects, medical applications	Arnaud Courvoisier (WIS)
	Antoine SNIJDERS (LBNL)

Table 1: list of speakers and contributors to the workshop

The THRILL consortium has installed a board representing the potential end-users in order to monitor the progress from this point of view throughout the entire project. The end-user board served as the scientific program committee and was composed of the following members, selected and appointed by the THRILL management board:

- Félicie Albert (LLNL, USA)
- Laurent Berthe (CNRS, France)
- Fazia Hannachi (University of Bordeaux, France)
- Dominik Kraus (University of Rostock, Germany)
- Kate Lancaster (University of York, UK)

1.2 Workshop program

The workshop took place in Ingelheim (Germany) on October 24-25, 2023.

On the first day of the workshop, a visit of the FAIR construction site was offered to all participants. The visit, which lasted 2 hours, was supported by the FAIR GmbH and gave the participants an idea about the size of the upcoming heavy-ion accelerator facility being built in Darmstadt.

Figure 1: picture of the visit of FAIR. Participants of the THRILL End-User Workshop visit the FAIR construction site in Darmstadt, Germany. [Picture: B. Zielbauer]

The scientific program of the meeting started with a welcome and introduction to the workshop (V. Bagnoud) and an introduction to the THRILL project (Zs. Major). The end-user board and the goals of the workshop were presented by D. Kraus. This was followed by two overview talks of the large-scale facilities FAIR and Eu-XFEL by K. Schoenberg and T. Cowan, respectively.

Following that, 15 scientific contributions summarizing the state-of-the art in laser-assisted experiments were given by prominent European and international scientist having direct hands-on experience running such experiments. Each contribution was the occasion for lively discussions, which was concluded by a general round table discussion and a closed session to give the boards the possibility to give feedback to the project management board.

Note that participation to the workshop in hybrid mode was possible, while more than 80% of the participants were on-site. The minutes of the round table discussion are given in the annex of this document.

2 Workshop report

2.1 Workshop introduction

The first two introductory contributions by K. Schoenberg, spokesperson of the HED@FAIR collaboration, and T. Cowan, spokesperson of the HIBEF consortium at Eu-XFEL, gave the participants the latest information on the two respective projects.

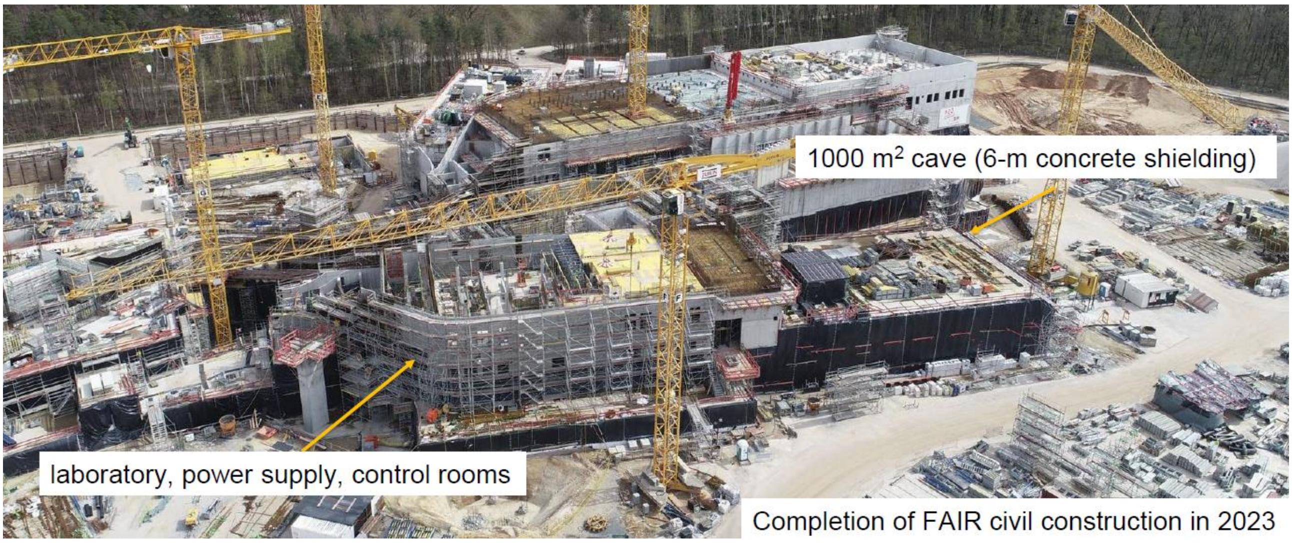

Figure 2: a bird's eye view of the HED installation at FAIR. [picture M. Konradt GSI/FAIR]

For HED@FAIR, the activities gravitate around pump-probe experiments, where the driver is the heavy-ion beam and the high-energy laser the probe. The civil construction for the high-energy-density (HED) experimental area is well under way, as seen in the picture from April 2023, Figure 2. However, delays incurred due to the international situation pushed the start of the experimental program of the HED@FAIR collaboration to the begin of the next decade. In the meantime, the collaboration will continue exploiting the existing facilities of GSI, including PHELIX. For the collaboration, the THRILL project comes very handy, as the FAIR delay gives the opportunity to explore and include new technological development into their experimental plans.

For HIBEF, the focus is now on the ramping up of the user operation at the HED target station at the Eu-XFEL, where first community experiments using the combination of optical lasers (as drivers) and the FEL as probe deliver results of extremely high quality. The HIBEF community is however strongly advocating to expand the laser capabilities towards a laser energy in the kilojoule range: the HIBEF 2.0 project. Here, the input of the workshop will be important in shaping the discussion with authorities.

The two ESFRI facilities Eu-XFEL and FAIR should not conceal that the field is driven by a large number of laser-stand-alone facilities, as APOLLON, OMEGA, and L4-Aton, just to mention those among the THRILL participants. Here also, the feedback of users is essential to define the R&D effort path to prioritize at these facilities that exist in an environment dominated by global scientific emulation.

2.2 Summary of scientific presentations

2.2.1 HEHRR lasers for warm-dense-matter research

Warm dense matter

Warm dense matter (WDM), defined as matter around solid-state density and temperatures in the 1-10 eV range, is a state of matter that is ubiquitous of planetary interiors, incl. the Earth, and therefore it plays a central role in astrophysics. Matter goes through the WDM state transiently during natural processes like high-velocity impacts (from space debris or meteorites) but also during laser-driven applications that run from femtosecond-laser machining to material hardening with laser (laser peening) and inertial confinement fusion processes.

In addition, WDM can be found to evolve on very different time scales from billions of years for astrophysical objects to the femto-microsecond range for man-made WDM states.

Warm dense matter generated by lasers in the laboratory

In the laboratory, it is possible to drive matter to WDM states with a nanosecond laser pulse. Here, the laser pulse heats the surface of a sample and the resulting ablation creates a pressure wave inside the target via momentum conservation. There results a compression (shock) wave located behind the ablation front that travels through the sample, reaching many Mbars and temperatures in the eV range.

In terms of the scaling laws for reaching WDM-relevant parameter ranges, the pressure depends on the laser intensity to the power of 0.67 to 0.75, with I = 10^{14} W/cm^2 yielding 10 Mbar as a rule of thumb (for a laser wavelength around 500 nm). In addition, the pressure depends inversely on the wavelength with a power of 0.25 to 0.67, meaning that a laser with a shorter wavelength exerts a higher pressure than for a longer wavelength at a given intensity.

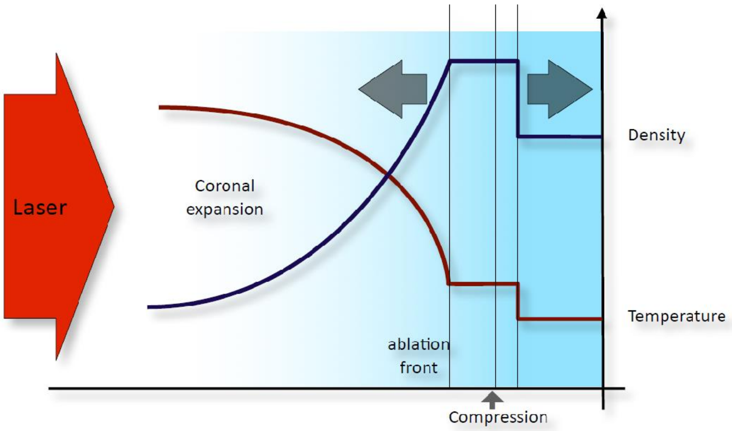

Figure 3: principle of the generation of WDM by shock compression with a laser pulse [contribution: T. Vinci].

The laser intensity (or power density) required to reach the WDM state can be used to derive the minimum necessary laser energy for such studies and successful proof of principle studies have been made in the past with as little as 10 J of energy in a nanosecond pulse and focused down to a 100-micrometer-wide spot.

Laser requirements for WDM studies

One complication arising from the use of shocks for studying WDM is the link between pressure and temperature, the so-called Hugoniot, which exists in a standard shock. In other words, the standard technique is limited to a specific area of the pressure-temperature phase diagram, which turns out to be away from WDM states of interest.

One way around that is the use of multiple shocks, which to the limit yields to adiabatic (shock-less) compression. This is the technique that is used nowadays and is considered state-of-the art. The drawback is that the multiple-shock timing requires pulses of much longer duration, up to 10 times longer than in the Hugoniot case. In addition, the longer pulse enables shocking thicker materials, i.e. more complicated targets. In particular, it is necessary to shield the cold material from pre-heating occurring at higher shock pressures by using thick layered targets. All this sums up to the requirement of **laser pulses in the 10-20 ns range**.

With the use of longer time scales comes the equally important need to increase the laser focal spot in order to maintain a quasi-1-dimensional plasma expansion and compression. Here, an increase of the spot size to ~ 0.5 mm seems necessary, which in turns gives an energy increase by a factor of 250 compared to the proof-of-principle case. This brings the **required laser energy in the kilojoule and even multi-kilojoule range**.

Ensuring a uniform laser illumination over the focal spot is necessary to create clean 1-dimensional expansion conditions. Traditionally, this is done by using a phase plate located close to the last focusing optics. It was stressed that the access to high-quality phase plates is essential in such experiments, to control the beam quality and, that it is not always granted at all laser facilities. The workshop participants discussed the use of discrete phase plates, which are standard in the community. While they are cost effective and easy to procure, their energy efficiency is not optimum. In the case of a kilojoule laser pulse, investments in continuous phase plates could be advantageous, as not to waste laser energy.

As far as the required number of shots for such studies, the workshop participants mentioned that already impactful WDM studies are performed at large-scale laser facilities like NIF and LMJ, with their share of advantages and inconveniences. Extreme pressures above 10 Mbars are in reach of the largest laser facilities but the number of shots available for WDM studies is extremely limited. Higher repetition rates (10 shots/day) are available at lasers in the energy range 0.1 - 100 kJ, but it is still not sufficient, while ultimately several factors limit the number of targets that can be shot during an experiment. These are:

- target fabrication and availability: since many targets are complicated, their fabrication and associated costs limit the number of targets available for a measurement campaign.
- target debris, especially at higher energies, and the consecutive target chamber pollution limit the amount of targets that can be shot during a single run.

WDM studies in the context of the EU-XFEL

Traditional diagnostics for shock experiments include measurements at the rear side of the target of the temperature and shock velocity, using surface optical pyrometry (SOP) and VISAR, respectively. The SOP delivers the WDM temperature under the assumption of back-body radiation, while the shock velocity can be linked to the WDM pressure.

Using the penetrating coherent radiation of the FEL enables new kinds of measurements that go beyond the traditional methods. First, the x-rays interact directly with the bulk on an atomic scale and enable a much more direct temperature measurements and secondly, x-ray imaging techniques yield a much more precise understanding of the experimental conditions. Therefore, there is an undeniable advantage of performing WDM studies at an FEL. This advantage is recognized widely among the scientific community, and therefore, other x-ray facilities like the ESRF, SACLA, LCLS are equipped by dedicated target stations. In addition, they are looking at upgrading their driving lasers with HEHRR lasers.

Speaker: T. Vinci

HEHRR laser for WDM

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Both driver and probing of WDM • Driver: compression to high density at moderate temp • Diagnostics: secondary x-ray creation: XRD of the WDM - What physics questions can be addressed with the methods? • For fundamental properties • Astro- and geophysics (exoplanets, planetary interior) • Material properties • ICF		
Limitations	- Laser parameter range available and which are the limitations imposed by these? • ns pulses, Intensity in the range of 10^{14} W/cm^2 • Scalability is not sufficient: Keep Intensity at same level while increasing pulse duration and energy or reducing both • Not all laser feature complex ns pulse shaping options • Lasers are not prepared to go HRR: shielding from projectiles (targets and optics)		
Future	- What laser parameters would be desirable, and would these make new physics accessible? • Long-Pulse shaping is KEY to access the phase diagram in a wide range • Energy is the main knob to reach these states. More energy is better. HE necessary to reach scientific goal • High stability in terms of pulse shape, energy and focal spot • HRR necessary to reach higher precision of measurements, especially if stability is not perfect • Facility parameter: Target support		
	Energy	ranges: good/still possible/not working	Ideally > 1kJ
		threshold for new physics	No specific threshold given
		role for scaling	Important
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	Not mentioned
		experiment over a long time (accumulation): stability important	Very important to reach same states in the phase diagram
		sufficient beamtime available at presently operational infrastructures?	Depends on the energy that is wanted. NIF-scale not sufficient, <=100J okay

		ranges: good/still possible/not working	still possible
	Pulse duration	threshold for new physics	Not specific, but some tens of ns would be good
		variability/pulse shaping necessary	Definitely very important
		role of spectral content	2w/3w useful to mitigate LPI and therefore pre heating of targets
	Temporal contrast	ranges: good/still possible/not working	Long pulse, so no requirements
		best possible or controlled?	-
	Beam quality	which aspects are important?	Stable beam profile
		importance of peak intensity?	Not that important
		Gauss - good enough? Other shapes - better?	Homogeneous → Phase plates

Speaker: D. Kraus
HEHRR laser for WDM

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • HE lasers are mostly used as drivers but also as diagnostics (when no XFEL is available) • Drive schemes ○ Shock compression (ns) ○ Isochoric heating with particles (ps) ○ Isochoric heating with soft x-rays (ns) ○ Implosions ns • Preferred diagnostics: XFEL; but kJ laser at XFEL is not available - What physics questions can be addressed with the methods? • Deeper understanding of WDM ○ Relevance of matter from Mbar to Gbar ▪ Evolution of stars/planets ▪ Classification of exoplanets ▪ Earth magnetic field ▪ Intense laser tech with application to material processing, fusion…
Limitations	- Laser parameter range available and which are the limitations imposed by these? • Typical laser parameters at compression exp at XFEL: ○ 15-60 J, ~10 ns square pulse drive laser • Pressures generation with lasers at XFELs (5ns, 200µm spot) ○ 20-30 J ○ ~10^{13} W/cm^2 ○ Repetition rate: shot per 10min up to 10 Hz • Short pulse lasers at XFEL ○ 1-10 J

	○ 25-40 fs ○ 1-5 Hz - Limits: • Pulse duration often limited to few ns, longer pulses would be interesting • kJ energy would be very interesting for both long and short pulses (>100 J also nice) • Some XRD need multi-kjJ beams to yield sufficient resolution and signal to noise in the results. Often more energy than the driver laser		
Future	- What laser parameters would be desirable and would these make new physics accessible? • Energy beyond kJ with pulse duration from few to some tens of ns. Also highly stable pulse shape as states must be reached precisely. Beam quality not as important because of PP usage • Short pulse (500fs – 10ps) with energy > 100J for snapshots • Repetition rate for sub kJ 10Hz or higher. For higher energy a shot per few minutes		
	Energy	ranges: good/still possible/not working	Still possible for some scenarios
		threshold for new physics	Not specified, but > kJ
		role for scaling	Important parameter
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	Quite a lot, as some states are hard to hit
		experiment over a long time (accumulation): stability important	Stability is an important parameter
		sufficient beamtime available at presently operational infrastructures?	No
	Pulse duration	ranges: good/still possible/not working	good
		threshold for new physics	Not specified
		variability/pulse shaping necessary	Long pulse shaping necessary
		role of spectral content	Not mentioned
	Temporal contrast	ranges: good/still possible/not working	Not mentioned
		best possible or controlled?	Not mentioned
	Beam quality	which aspects are important?	
		importance of peak intensity?	Not mentioned
		Gaussian - good enough? Other shapes - better?	PP for multi kJ backlighter, small spot size for snapshots with short pulse

2.2.2 HEHRR lasers for high-field quantum electrodynamics

Quantum electrodynamic studies with lasers

Quantum electrodynamics (QED) describe the phenomena where charged particles, e.g. electrons or positrons interact by the means of photons. In a nutshell, QED studies with lasers deal with physics up to the Schwinger light intensity limit of ~ 10^{29} W/cm^2. While such intensities are not readily available in the laboratory – the highest intensity ever measured was 10^{23} W/cm^2 [1] - , this gives a first hint that the laser intensity is the main concern for this field of study.

A flagship experiment of the HIBEF consortium at the Eu-XFEL aims at measuring birefringence effects in the vacuum, which is a nonlinear effect predicted by QED theory. The experimental setup deals with a x-ray probe beam from the FEL that interrogates a region of the vacuum, where a high-intensity laser is focused. Here the effect will be very small, typically of the order of 1:10^{-13}. This has two implications: first the apparatus needs to resolve this effect and offer the required precision, second the number of scattered photons will be very small, typically of the order of 0.1 photon per shot, at the current FEL photon flux. In terms of apparatus, the modern x-ray polarizers developed at HI Jena in Germany seem to fulfill these requirements. However, the signal will be very small and requires accumulating shots to improve the signal-to-noise ratio. The dependency of the signal is linear with the FEL flux and quadratic with the intensity.

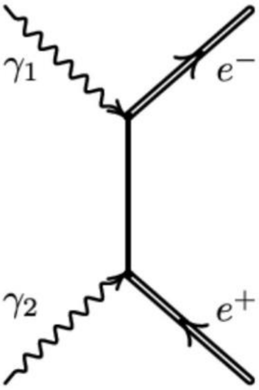

Figure 4: Feynman diagram of electron-photon scattering (non-linear inverse Compton scattering)

Beyond proof-of-principle experiments, impactful physics experiments need to offer a level of precision in measurement close to 10^{-5} to enter the realm of theory corrections that can make sense for a physics program at the Eu-XFEL. At the expected signal-to-noise ratio, this puts an even stronger requirement on the laser and rules out single shot lasers.

Other QED experiments include all-optical experiments that can be performed at a laser facility. In this scheme, an electron beam is generated by a laser via laser wakefield acceleration (LWFA) and interacts with optical beam to generate gammas (inverse Compton scattering), which can decay in the laser field into positron and electron pair (Breit-Weehler process). In this type of experiment, the laser intensity plays an important role, and it is essential to work at least at 10^{21} W/cm^2 or above, for the optical laser part. Note that some additional requirements arise for the laser beam dedicated to the electron production. Such experiments are conducted worldwide e.g. at the Astra-Gemini facility in the UK.

Lastly, it should be mentioned that ultra-high intensity lasers, like at ELI-NP, have proposed experiments for the search of particles beyond the standard model, like axions, via photon-photon interactions. This requires in turn extremely high average powers and accumulation times.

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[1] Yoon, Jin Woo, et al. "Realization of laser intensity over 10^{23} W/cm^2." *Optica* 8.5 (2021): 630-635.

Laser requirements for QED studies

The foremost parameter is the laser on-focus intensity. Here, the discussed threshold is 10^{21} W/cm^2, above which such experiments can be conceived. Therefore, a peak power above 1 petawatt seems a minimum requirement with some emphasis on the recently-commissioned 10-PW laser facilities. So a requirement for such type of experiments done with a HEHRR laser calls for **multi-petawatt peak power**.

In addition to the peak power, **the quality of the laser beam needs to be excellent**, such as to avoid a reduction of the in-focus laser intensity. Usually, beam quality can be described in terms of the Strehl ratio (SR<1), that describes the loss of intensity at the focus of a laser because of its beam quality distortion. In other words, a SR of 0.5 yields a reduction of the available peak laser intensity for a given laser peak power, which in turns reduces the signal by a factor 4. Emphasis on beam quality came in the discussion, not only because of the intensity, but also by the **spatial beam pointing stability** imposed by the multi-beam nature of QED experiments. So a laser used for this application should not trade beam quality for energy, as the efforts to produce more energetic pulses would be cancelled by the beam degradation.

The repetition rate of the laser important for QED experiments, either for signal-to-noise ratio reasons or just because the source generated needs to have a reasonable average power. The group discussed that a **10 Hz repetition rate for a 10 PW laser** would be ideal for the birefringence experiment of the HIBEF consortium, which sets a very ambitious goal for HEHRR lasers. For other QED experiments, lower requirements exist. In the discussion, a repetition rate close to 1 Hz seems to be an ideal goal to be pursued.

Speaker: M. Zepf
HEHRR laser for probing QED vacuum

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Laser as driver to generate nonlinearity in vacuum and XFEL to probe the vacuum nonlinearity • Laser to generate electron beam and high energy photons in other case - What physics questions can be addressed with the methods? • Fundamental QED properties of the vacuum • Nonlinear corrections to the quantum vacuum field
Limitations	- Laser parameter range available and which are the limitations imposed by these? • Lasers can cover the necessary intensity, energy, peak power • Lasers lack in average power which is necessary to reach the wanted precision of the experiments • Lasers furthermore are not stable enough which further reduces the precision

Future	- What laser parameters would be desirable and would these make new physics accessible? • Repetition rate: ○ Ideal: 10 Hz, 10 PW. However, problematic to stabilize ○ Alternative 1) 27 kHz, 1-10 J ○ Alternative 2) MHz, 30 mJ (via cavity enhancement lasers?) • Pulse duration: ○ Ps pulse may scale better than fs pulses, as the interaction range increases 200J, 450 fs, 100Hz – kHz would be nice to reach precision		
	Energy	ranges: good/still possible/not working	Energy possible, but not with specified average power
		threshold for new physics	No specific threshold
		role for scaling	Effect if field/ intensity dependent
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	thousands
		experiment over a long time (accumulation): stability important	Stability is important, as reduced stability increases accumulation time
		sufficient beamtime available at presently operational infrastructures?	Only CALA and XFEL mentioned
	Pulse duration	ranges: good/still possible/not working	good
		threshold for new physics	No specific threshold mentioned
		variability/pulse shaping necessary	Not mentioned specifically, high peak power necessary
		role of spectral content	Short pulse, so > few nms at min
	Temporal contrast	ranges: good/still possible/not working	Not mentioned, but as the peak intensity barely has any effect, contrast will probably not be an issue
		best possible or controlled?	
	Beam quality	which aspects are important?	Beam Strehl will effectively reduce interaction. SO high Strehl is desired
		importance of peak intensity?	High importance
		Gauss - good enough? Other shapes - better?	Not special shaping mentioned

Speaker: E. Los
HEHRR laser for QED studies

<table>
<tr><td>State-of-the-art</td><td colspan="3">- What are high power lasers used for in the field (drivers, diagnostics)?
• Lasers used to drive secondary sources which are then used in the experiment
• Secondary sources are fast electrons (generated via LWA) and x-rays (via inverse bremsstrahlung)
- What physics questions can be addressed with the methods?
• Investigation of high-field effects such as linear and nonlinear Breit-wheeler process</td></tr>
<tr><td>Limitations</td><td colspan="3">- Laser parameter range available and which are the limitations imposed by these?
• Limitations due to repetition rate and stability of the laser in terms of pointing and jitter</td></tr>
<tr><td>Future</td><td colspan="3">- What laser parameters would be desirable, and would these make new physics accessible?
• Laser 1 (wakefield driver) maximum energy in FWHM (good focal spot shape), pulse duration 35 fs, long focal length, high rep
• Laser2) for Nonlinear Breit-Wheeler
○ high intensity and stable in intensity, small spot size (2µm) , pulse duration < 30 fs, linearly polarized
• Laser2) for linear Breit-Wheeler (x-ray production)
○ 50ps, 2µm spot, high energy beneficial, as spot size could be increased, high ns contrast, ps contrast must not be that high, smooth beam profile with PP (contradiction with small spot size?)</td></tr>
<tr><td rowspan="7"></td><td rowspan="3">Energy</td><td>ranges: good/still possible/not working</td><td>Not specifically mentioned, seems to be less problematic</td></tr>
<tr><td>threshold for new physics</td><td>Not mentioned</td></tr>
<tr><td>role for scaling</td><td>Not mentioned</td></tr>
<tr><td rowspan="3">Repetition rate</td><td>single-shot experiments: how many shots are necessary for meaningful experiment?</td><td>Too many</td></tr>
<tr><td>experiment over a long time (accumulation): stability important</td><td>Stability very important and high rep also to be able to use modern analysis methods such as machine learning. > 1Hz would be nice</td></tr>
<tr><td>sufficient beamtime available at presently operational infrastructures?</td><td>Only experiments at Gemini</td></tr>
<tr><td>Pulse duration</td><td>ranges: good/still possible/not working</td><td>There are quite some facilities that can provide such pulse duration, so probably good. Yet, still demanding</td></tr>
</table>

		threshold for new physics	Not mentioned
		variability/pulse shaping necessary	Not mentioned
		role of spectral content	Not mentioned
	Temporal contrast	ranges: good/still possible/not working	Not important for nonlinear Breit-Wheeler experiments. Ns contrast important for linear Breit-Wheeler experiments.ps contrast may be used to enhance coupling into plasma
		best possible or controlled?	controlled
	Beam quality	which aspects are important?	Small spot size, but homogeneously
		importance of peak intensity?	Very important
		Gauss - good enough? Other shapes - better?	Smooth beam profile

2.2.3 HEHRR lasers for magnetic field generation

Optically magnetized plasma

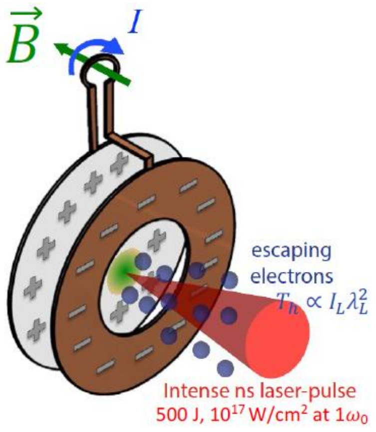

Figure 5: principle for a B-field generation with a nanosecond laser , pulse [Santos et al., New J. Phys. ***17****, 083051 (2015)]*

Strongly magnetized plasmas behave differently as the magnetic field changes the electron thermal conductivity, the plasma hydrodynamics and atomic physics. Here, the field of applications ranges from understanding astrophysical objects, collisionless shocks, plasma jets and magnetic reconnection. In particular, neutrons stars sustain extreme magnetic fields of 100 kT to 100 MT. In addition, magnetized plasma could find a very interesting application in inertial confinement fusion for magnetized implosion studies.

It is possible to create intense transient magnetic fields with lasers. A desirable effect is the possibility to generate a rapid spatial charge separation with an impinging laser pulse, which is followed by a fast neutralization current. By choosing the right geometry, the magnetic field can be tailored to one's own needs. Given the amount of free carrier scales with the laser energy, higher pulse energies relate to strong magnetic fields. In recent studies of the last 5 years, fields in the 0.1 - 1 kT range were obtained with 1 kJ of energy and nanosecond pulse durations. However, it could be desirable to push this above the kilotesla limit.

The field of magnetized plasma studies is still relatively new and in development. More experimental data is necessary to benchmark simulation codes. The community has the right tools to study the generation of intense magnetic fields with lasers as diagnostics using polarimetry, laser-driven proton radiography and Zeeman spectroscopy. Many experimental schemes rely on the availability of several laser beams with fundamentally different laser parameters used as drivers on one hand, and diagnostic tools on the other.

Laser requirements to generate and study magnetic fields

In such experiments, the energy is the parameter that seems to play the most important role, with the immediate goal to generalize experiments in the **kilojoule range**, while no real threshold exists for this application. A peculiar requirement for such an experiment calls for **a dedicated auxiliary beam**, which for plasma physics experiment means more than 2 beams, as the first two beams are usually dedicated to the plasma pump-probe setup.

The required intensity to drive the effects remains moderate, in the 10^{15}-10^{17} W/cm^2 range. Here, the upper part of the interaction range still needs to be investigated, as it is well known to be prone to laser-plasma instabilities, which could influence the magnetic field generation in an uncontrolled manner. As the intensity required to drive the charge separation is not very critical, such a laser beam can tolerate some beam distortion. In addition, it may be required to maintain the magnetic field over some time and the dedicated laser should then have a pulse duration in the nanosecond range.

The setup to create a magnetized plasma involves 3-dimensional targets that are disposed after every laser shot and need to be replaced. This is a large limitation for the repetition rate of the experiment and therefore relaxes the need for the laser to reach extremely high repetition rates. This application will therefore not benefit as much from the high-repetition-rate development within the THRILL project, as some of the other applications described in this document.

The parameters of the lasers used for diagnostics are situated in an entirely different range. Here, high intensity (> 10^{20}W/cm^2) is required in short pulses to drive for example a source of protons for radiography.

Speaker: J. J. Santos
HEHRR laser for magnetic field generation

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • They are used as a driver for generating high magnetic fields - What physics questions can be addressed with the methods? • Laser driven coil target (LDC) are an all-optical (quasi) debris free platform for delivering external B-fields to laser-plasma exp. • Experiments have successfully used LDC for studying magnetized plasma phenomena such as relativistic electron transport, hydro instability growth rate, collisionless shocks, plasma jets and magnetic reconnection
Limitations	- Laser parameter range available and which are the limitations imposed by these? • LULI2000: 500 J, 1-ω, 1 ns (FT) -> 10^{17} W/cm^2 -> 800T@peak • GEKKO-LFEX: 1.8 kJ, 1-ω, 1.2 ns (G) -> 7 . 10^{15} W/cm^2 -> 600T@peak • OMEGA-EP: 5 kJ, 3-ω, 10 ns (FT) -> 2 . 10^{15} W/cm^2 -> 200T@peak • OMEGA: 1.3 kJ, 3- ω, 1 ns (FT) -> 3 10^{16} W/cm^2 -> 50T@peak • LMJ: 12 kJ, 3- ω, 3 ns (FT) -> 2 . 10^{15} W/cm^2 -> 3T@peak

Future	- What laser parameters would be desirable and would these make new physics accessible? • LPI at the explored/required laser intensities (ns-laser with >10^{15} W/cm²) is poorly known (scaling laws are required!) • It is not yet demonstrated that LDC can deliver B-fields in the kT range • It is important to reach highest laser intensity at kJ-level energy (preferably at higher laser wavelength). • Proposed laser parameters: 10^{17} W/cm² over ns • kJ-level laser energy would be amazing		
	Energy	ranges: good/still possible/not working	ns-laser with >10^{15} W/cm²
		threshold for new physics	kJ-level energy would be amazing
		role for scaling	Scaling poorly understood
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	Not mentioned (limited by target alignment / production?)
		experiment over a long time (accumulation): stability important	Not mentioned
		sufficient beamtime available at presently operational infrastructures?	Not mentioned
	Pulse duration	ranges: good/still possible/not working	longer pulses (ns) required to get to the peak/optimal current
		threshold for new physics	Not mentioned
		variability/pulse shaping necessary	Not mentioned
		role of spectral content	Not mentioned
	Temporal contrast	ranges: good/still possible/not working	Not mentioned
		best possible or controlled?	Not mentioned
	Beam quality	which aspects are important?	Not mentioned
		importance of peak intensity?	Not mentioned
		Gauss - good enough? Other shapes - better?	Not mentioned

Speaker: N. Woolsey
HEHRR laser for magnetic field generation

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Long pulse lasers to implode cylinders/spheres to converge magnetic field lines and reach higher B-fields • Short pulses to generate fast electrons which create a high B field while passing through solid medium • HHG to probe coronal fields • Generation of colliding magnetic fields to use reconnection as an acceleration mechanism • Use laser accelerated protons for proton imaging of reconnection

<table>
<tr><td></td><td colspan="3">- What physics questions can be addressed with the methods?
• Magnetized HED important for ICF, electron beam guiding in fast ignition), IFE, astrophysics (shocks, neutron star envelops), planetary interiors, WDM, particle acceleration (Magnetic reconnection)
• Testing of computational tools</td></tr>
<tr><td>Limitations</td><td colspan="3">- Laser parameter range available and which are the limitations imposed by these?
• Used lasers are Vulcan PW and Orion laser</td></tr>
<tr><td>Future</td><td colspan="3">- What laser parameters would be desirable and would these make new physics accessible?
• kJ energy necessary
• ideally two laser beams
• long pulses: > 5 ns
• high intensity: > 10^{20}W/cm^2
• large focal spots - use of phase plates?
• High rep rate for parameter scans
• Diagnostics: x-ray, optical and particle</td></tr>
<tr><td rowspan="18"></td><td rowspan="3">Energy</td><td>ranges: good/still possible/not working</td><td>>kJ. still possible but HRR will be hard</td></tr>
<tr><td>threshold for new physics</td><td>Not mentioned specifically, but >= kJ</td></tr>
<tr><td>role for scaling</td><td>Important</td></tr>
<tr><td rowspan="3">Repetition rate</td><td>single-shot experiments: how many shots are necessary for meaningful experiment?</td><td>Not mentioned</td></tr>
<tr><td>experiment over a long time (accumulation): stability important</td><td>High stability beneficial as otherwise longer accumulation is needed. HRR for parameters scans desired. No specific number</td></tr>
<tr><td>sufficient beamtime available at presently operational infrastructures?</td><td>Not mentioned specifically, experiments at Orion and Vulcan PW</td></tr>
<tr><td rowspan="4">Pulse duration</td><td>ranges: good/still possible/not working</td><td>good</td></tr>
<tr><td>threshold for new physics</td><td>Not mentioned</td></tr>
<tr><td>variability/pulse shaping necessary</td><td>Not mentioned</td></tr>
<tr><td>role of spectral content</td><td>Not mentioned</td></tr>
<tr><td rowspan="2">Temporal contrast</td><td>ranges: good/still possible/not working</td><td>Not mentioned</td></tr>
<tr><td>best possible or controlled?</td><td>Not mentioned</td></tr>
<tr><td rowspan="3">Beam quality</td><td>which aspects are important?</td><td>Large focal spots, no specific shape mentioned</td></tr>
<tr><td>importance of peak intensity?</td><td>10^{20}W/cm^2 mentioned. However, somewhat contradicts long pulse and large focal spot</td></tr>
<tr><td>Gauss - good enough? Other shapes - better?</td><td>Not mentioned</td></tr>
</table>

2.2.4 HEHRR lasers for dynamic compression of materials

Materials under dynamic compression

Materials under high pressure and temperatures, typically in the area before they enter the WDM state, around 1 Mbar and 1000 K, undergo phase transitions that are of interest to geoscience and a wide range of material science applications, for which materials are exposed to harsh conditions like turbines and engines. Such a state of matter can be reached advantageously with lasers, running shocks and/or adiabatic compression with nanosecond lasers.

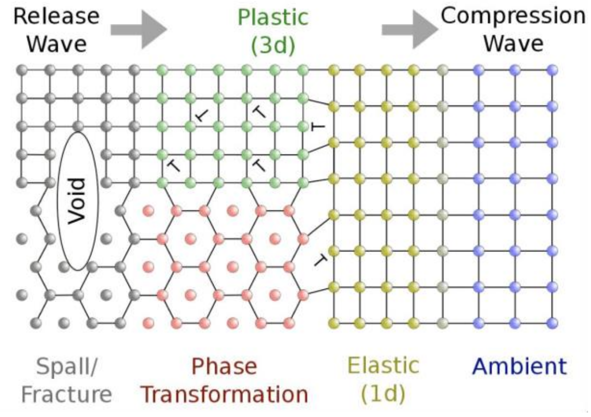

Figure 6: the dynamics of material deformation under laser compression. [Contrib. A. Higginbotham]

Laser-driven material compression is interesting due to the volumes that can be addressed by this method. The volume is defined by the focal spot, typically some 100 micrometers in the transverse dimensions and tens of micrometers in depth. Real materials are often made of multiple crystals with a scale range of several tens of micrometers. They are not homogeneous and can exhibit defects on the micrometer scale. This adds a dimension of complexity to high-pressure phase diagrams that are already complex on the atomic scale. Such microscopic material properties include also anisotropy. In addition, their response to strain rates, which is important in real-life applications must be understood with dynamical experiments. All that justifies this field of research, which explores areas not accessible by other well established compression methods.

The advent of XFELs has pushed this field of research forward as the x-ray sources of coherent radiation enable time-resolved imaging studies at the atomic scale. The XFEL delivers the snap shots necessary to understand the material phases and their transition dynamics in the most accurate way.

Laser requirements for dynamic compression studies

In essence, the experimental setup is similar to the one used in WDM studies, with a drive laser and a FEL used as probe. However, the energy required to reach the somehow lower pressure is not as high as in the previous case. The existing high repetition rate lasers like DiPOLE at Eu-XFEL are already very well performing. Extending the energy to the kilojoule range will definitely improve the range of parameters accessible. In particular, operation with pulses up to 20 ns could be advantageous.

One essential aspect of this type of studies resides in the large number of shots necessary to map the phase space of a wide variety of materials. Therefore, operation repetition rates up to **10-Hz repetition rate** could be advantageous, especially in the context of the Eu-XFEL, which enables faster scans and turning over samples quickly. Here, one must stress that this is a strong technical requirement, and that data sets could be obtained at lower repetition rates, between 1 shot/min to 1 Hz. Higher repetition rates than 10 Hz are probably not realistic, as target handling limits the operation right now.

Most importantly, **laser pulse and beam stability** are very important to ensure stable compression conditions. The group discussed that stability of the laser parameters at the percent level is essential. High-fidelity pulse shaping and control is essential to precisely control the area of the pressure-temperature phase diagram under exploration. In addition, working with higher energies improves the focal spot fluctuations due to phase plates.

Speaker: A. Higginbotham

HEHRR laser for dynamic compression of materials

<table>
<tr><td>State-of-the-art</td><td colspan="3">- What are high power lasers used for in the field (drivers, diagnostics)?
• Lasers are used to generate shocks in samples to study material across a range of p-T states
- What physics questions can be addressed with the methods?
• Material science
• Geo/astrophysics?</td></tr>
<tr><td>Limitations</td><td colspan="3">- Laser parameter range available and which are the limitations imposed by these?
• Extreme pressured limited to Omega/NIF etc.
• DIPOLE has opened up new avenues for XFEL science (Most detailed studies coming from XFELs)</td></tr>
<tr><td>Future</td><td colspan="3">- What laser parameters would be desirable and would these make new physics accessible?
• 10 Hz (limited by samples refresh rate?)
• Percent level beam profile stability (temporal and spatially)
• High fidelity pulse shaping to reach various p-T states
• On-the-fly pulse shape optimization (machine learning) -> high rep. rate!
• Higher energy to increase pressure or larger drive spot
• Longer (>20ns) pulses to enable more diverse kinetics studies</td></tr>
<tr><td rowspan="6"></td><td rowspan="3">Energy</td><td>ranges: good/still possible/not working</td><td>Not mentioned</td></tr>
<tr><td>threshold for new physics</td><td>Not mentioned</td></tr>
<tr><td>role for scaling</td><td>Not mentioned</td></tr>
<tr><td rowspan="3">Repetition rate</td><td>single-shot experiments: how many shots are necessary for meaningful experiment?</td><td>Percent level beam profile stability (temporal and spatially)
Enable on-the-fly optimization (machine learning)</td></tr>
<tr><td>experiment over a long time (accumulation): stability important</td><td>Not mentioned</td></tr>
<tr><td>sufficient beamtime available at presently operational infrastructures?</td><td>Not mentioned</td></tr>
</table>

	Pulse duration	ranges: good/still possible/not working	Longer (>20ns) pulses to enable more diverse kinetics studies
		threshold for new physics	
		variability/pulse shaping necessary	
		role of spectral content	Not mentioned
	Temporal contrast	ranges: good/still possible/not working	Not mentioned
		best possible or controlled?	Not mentioned
	Beam quality	which aspects are important?	Percent level beam profile stability (temporal and spatially)
		importance of peak intensity?	Not mentioned
		Gauss - good enough? Other shapes - better?	Not mentioned

2.2.5 HEHRR lasers for nuclear photonics

The field of nuclear photonics

Nuclear photonics can be described as the combination laser and plasma physics with nuclear physics and accelerator science. This field is very recent and has emerged as laser performances have reached the petawatt level and above.

By shining a laser onto a sample, extreme conditions of temperatures and pressures (100 eV, solid state density) could be applied for a long enough time to trigger nuclear excitations by electron transitions or captures (NEET/NEEC), showing the coupling between the electronic and nucleus structures of atoms. This is a rather unique example of a direct interaction with the laser, which in this case is a nanosecond kilojoule laser. In addition, only a small number of nuclei with close isomeric states can be addressed, e. g. ^{84m}Rb, which introduces an additional complication.

In other experiments, the laser replaces the conventional accelerator for the production of short bunches of electrons, ions or secondary neutrons. Such intense particle bunches are relevant to the r-process nucleosynthesis for instance, with a very rich discovery potential. As far as using laser-accelerated ions, there exists a strong interest to push the development and improve the energy of the ions as well as their average flux. This is motivated by the extremely high instantaneous ion fluxes reached by the laser-driven ion bunch. On this path, a complication comes from the Coulomb barrier that needs to be overcome to trigger nuclear processes. This limit is in general around 10 MeV/u for the particle kinetic energy.

The last area of research and development in nuclear photonics deals with neutron production. Here, one could take advantage of the somehow compact source and pulsed operation mode to develop new devices and interrogation methods.

Laser requirements for nuclear photonics

In Europe, nuclear photonics is the central research focus of ELI-NP. There, the performance of the lasers are still being ramped up and the experimental areas brought into operation. This laser in the **multi-petawatt range**, as well as others of the same class, have the necessary characteristics to explore ion acceleration driven by intensities in the **10^{22} - 10^{23} W/cm^2 range**, where experimental data is scarce, and simulations predict efficient acceleration schemes.

For such experiments that include the interaction of an ultra-high-intensity laser pulse with solid targets, the temporal behavior of the laser pulse must be controlled over more than 13 orders of magnitude, which is still an active topic of laser development. This, however, is beyond the scope of research of the THRILL project.

Speaker: P. Thirolf
HEHRR laser for nuclear photonics

<table>
<tr><td>State-of-the-art</td><td colspan="3">- What are high power lasers used for in the field (drivers, diagnostics)? Laser driven ion bunches (p to Au, future U?)
- What physics questions can be addressed with the methods?
Nuclear photonics, r-process isotopes, NEET/NEEC, nuclear reactions in plasmas, neutron production</td></tr>
<tr><td>Limitations</td><td colspan="3">- Laser parameter range available and which are the limitations imposed by these? Pulse energy (10-few 100 J) limits ion yield; Reprate (few/day-1Hz) slows R&D, limits statistics; pulse duration (25-500 fs) limits acceleration mechanism</td></tr>
<tr><td>Future</td><td colspan="3">- What laser parameters would be desirable and would these make new physics accessible? Pulse energy (good 100-1000 J, possible: 50-100 J, threshold for new physics: few 100 J on target</td></tr>
<tr><td rowspan="11"></td><td rowspan="3">Energy</td><td>ranges: good/still possible/not working</td><td>good 100-1000 J, possible: 50-100 J</td></tr>
<tr><td>threshold for new physics</td><td>threshold for new physics: few 100 J on target</td></tr>
<tr><td>role for scaling</td><td></td></tr>
<tr><td rowspan="3">Repetition rate</td><td>single-shot experiments: how many shots are necessary for meaningful experiment?</td><td>5-10 shots</td></tr>
<tr><td>experiment over a long time (accumulation): stability important</td><td>10^4-10^5 shots, drift stability, pointing < Rayleigh length</td></tr>
<tr><td>sufficient beamtime available at presently operational infrastructures?</td><td>large request overdraft</td></tr>
<tr><td rowspan="4">Pulse duration</td><td>ranges: good/still possible/not working</td><td>20-50 fs</td></tr>
<tr><td>threshold for new physics</td><td>focused intensity >10^{23} W/cm^2 (RPA)</td></tr>
<tr><td>variability/pulse shaping necessary</td><td>controlled pre-pulse for plasma pre-expansion</td></tr>
<tr><td>role of spectral content</td><td></td></tr>
<tr><td></td><td>ranges: good/still possible/not working</td><td>10^{13} (w/o plasma mirror)</td></tr>
</table>

	Temporal contrast	best possible or controlled?	
	Beam quality	which aspects are important?	flat wave front for optimum focus, Strehl > 0.6
		importance of peak intensity?	
		Gauss - good enough? Other shapes - better?	

2.2.6 HEHRR lasers for medical applications

Medical applications

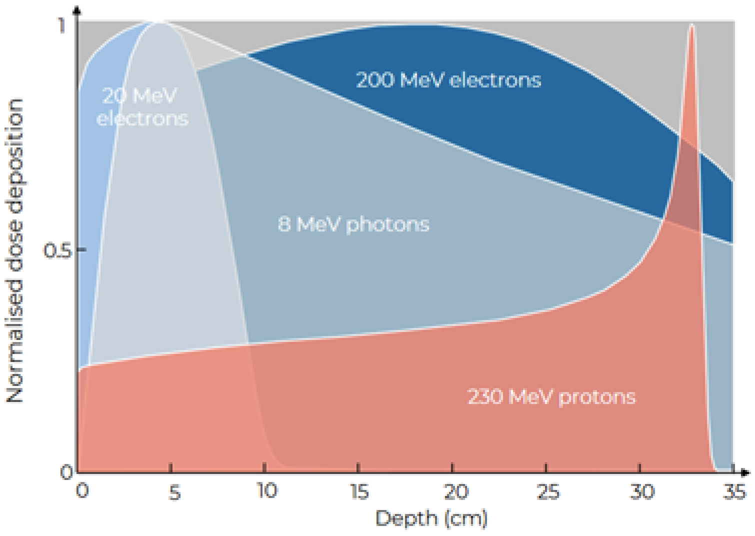

Figure 7: dose deposition for electron, X-ray and proton beams as a function of propagation depth. [Contrib. A. Courvoisier]

An important application of HEHRR lasers is that of medical applications. In radio-oncology, particle and X-rays are used for cancer treatment. While electrons and X-rays from conventional linear accelerators are routinely used in the treatment protocols of various forms of cancer due to their availability, ion-beam therapy shows a number of advantages, in particular the possibility of tailored energy deposition in the cancerous tissue while the dose on healthy tissue is kept low. Despite these promising characteristics of ion beams for therapy, the technique is not widely available to patients, as the technical realization requires large-scale infrastructures and is therefore expensive.

Owing to these limitations, the idea of using HEHRR lasers for driving secondary electron, X-ray or (light) ion sources, has been motivating this direction of research for the last couple of decades. In particular for the case of ion beams, the laser-driven sources are much more compact and cost-effective compared to conventional accelerator technology. However, the challenges here lie in the stability and reproducibility of the generated ion pulses. On the other hand, the ultrashort duration of laser-driven ion pulses allows the deposition of several orders of magnitude higher dose rates as compared to conventional machines. This allows for the so-called FLASH-effect to become relevant, where the time scale on which the dose is deposited becomes crucial to the effect on the healthy tissue and is shown to reduce detrimental effects and complications during treatment.

In addition to ion-beam therapy, high-energy, laser-accelerated electrons show promising characteristics for radiotherapy and are currently being investigated, e.g. in the framework of the EU-funded project “ebeam4therapy”. Here the necessary dose rate is achieved by the high repetition rate, at which it is possible to generate the necessary electrons. The relatively low energy, but ultra-intense lasers, as well as the gas-jet or gas-cell-based targets allow for several Hz operation.

Laser requirements for medical applications

Using laser-accelerated ion beams for therapy is currently being explored on animal models. At the BELLA facility (Berkeley) protons are used in the energy range of 2-7 MeV/u, while other facilities, e.g. DRACO in Dresden use 25-30 MeV/u. The clinically relevant range of ion energies lies at 200 MeV/u for tumors within the body and 50-100 MeV/u for more easily accessible ones or close to the surface. In any case, the driver laser needs to be scaled up from the currently available **40 J, 45 fs** pulse duration and a repetition rate of **1 Hz**.

In the case of high-energy electron beams the pulse duration of a few 10s of fs is similar, but the requirements on energy are much lower (J-scale). However, in order to reach a clinically relevant dose of 1Gy/s, **100 Hz** operation is necessary.

In all cases of medical applications, the main requirements of the laser systems are **reproducibility and stability**. In conclusion, the laser requirements for medical applications call for much shorter pulses, with lower energy but significantly higher repetition rate than envisaged in the THRILL project. Therefore, this application will not represent one of the main direction of development.

Speakers: A. Snijders, A. Courvoisier

HEHRR laser for Radiotherapy

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? - What physics questions can be addressed with the methods? • Drivers for radiotherapy ion sources		
Limitations	- Laser parameter range available and which are the limitations imposed by these?		
Future	- What laser parameters would be desirable and would these make new physics accessible?		
	Energy	ranges: good/still possible/not working	Higher is better. Higher laser energy -> higher proton/ion energy
		threshold for new physics	
		role for scaling	
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	100s to 1000s of shots per day
		experiment over a long time (accumulation): stability important	1 Hz, stability extremely important over hours (or days)
		sufficient beamtime available at presently operational infrastructures?	There are very few laser proton sources for medical applications. BELLA in US, one or two in UK, one or two in Germany and Czech Republic.

	Pulse duration	ranges: good/still possible/not working	optimal: 10s to 100s of fs
		threshold for new physics	
		variability/pulse shaping necessary	Pulse shaping is beneficial to tune the proton/ion source
		role of spectral content	
	Temporal contrast	ranges: good/still possible/not working	
		best possible or controlled?	Controlled ranges
	Beam quality	which aspects are important?	shot-to-shot stability, potential kHz development
		importance of peak intensity?	broad ion energy spectrum might be useful if properly tuned
		Gauss - good enough? Other shapes - better?	optimal 50-100 MeV protons

2.2.7 HEHRR lasers for inertial fusion energy

Laser-driven inertial confinement fusion (ICF) research and inertial fusion energy (IFE)

Laser-driven ICF has received a great deal of interest beyond the scientific community, thanks to the communication happening around the experimental results announced at the National Ignition Facility (NIF) in the USA. In their experimental campaigns, the scientists at NIF are using 192 laser beams of UV light focused into a hohlraum, which in turns create x-ray radiation that compress a deuterium-tritium (DT) sphere to conditions where DT fusion can start and sustain itself. While the laser installation was operational in 2009, it took until 2018 until the first signs of significant fusion reactions became obvious [2] and another 3 years to publish evidence of fusion burn [3], defined as fusion reactions able to sustain themselves inside the assembled DT fuel. What received the public attention, is the demonstration of “scientific breakeven” that was advertised by the Lawrence Livermore National Laboratory in 2022. That means that the assembled DT fuel capsule inside its hohlraum produced more fusion energy than the laser energy used to drive this reaction.

This major milestone opens a new field of application for HEHRR lasers, namely the production of inertial fusion energy (IFE) that holds promise of nearly unlimited amounts of carbon-free energy. While THRILL has been conceived and applied for at the European Commission before the latest breakthrough in ICF research, lasers for IFE and basic research share a lot of commonalities.

The international community is actively discussing what the next steps in IFE could be. One immediate goal is the demonstration of target gains around 30 to 50, which would enable thinking of a test facility that could be self-sustainable energetically. This can be either reached via brute force (more laser energy), and/or optimization of the laser, laser-plasma interaction and target. The latter

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[2] Hurricane, O. A., et al. "Approaching a burning plasma on the NIF." *Physics of Plasmas* **26**.5 (2019).

[3] Zylstra, A. B., et al. "Burning plasma achieved in inertial fusion." *Nature* **601**.7894 (2022): 542-548.

receives interest in the community, incl. from the private sector.

Laser requirement for ICF research

Looking at ICF research, the community pleads for the construction of a multi-beam compression facility that should enable testing new ideas in ICF at a scale that is at or close enough to an ignition facility. The order of magnitude for the energy is 100 kJ, which will be spread over tens of beams and the horizon of such a facility would be 5-10 years, so well beyond the THRILL project end. Such lasers are nanosecond high-energy lasers, which should include the latest improvements in laser technology. That would support also the consensus to move away from single shot experiment and that a certain shot rate, similar to the solution sought after by THRILL, could be essential en-route to a proven ICF facility concept.

In parallel to ICF research, the goals for IFE must be urgently worked on, as they are much more stringent for the laser than in the case of ICF research. These goals can be summarized by: 1. having a laser with a 7-to-20% wall-plug efficiency and 2, having a laser capable of 10 Hz operation. While THRILL never ambitioned solving such problems within the project time frame and budget, the group stressed the synergetic effect that THRILL could have in IFE research and development.

Speaker: L. Masse
HEHRR laser for ICF

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Drivers for ICF • XFEL as diagnostic? - What physics questions can be addressed with the methods? • How to get energy out of nuclear fusion
Limitations	- Laser parameter range available and which are the limitations imposed by these? • NIF (only indirect drive, low rep rate) • LULI and Omega are essential to test ideas
Future	- What laser parameters would be desirable and would these make new physics accessible? • DD more energy efficient than ID, simulations predict today that hundreds of kJ should be enough; aiming for a MJ call facility is a safe bet • Before that, a kJ to 10 kJ laser would be great help (LULI and Omega are essential to test ideas) • Pulse shaping (high fidelity) • Long duration (>10 ns) • Different wavelength to test (2,3,4,… omega) • Platform to test smoothing schemes • Different phase plates • Symmetrical geometry to test compression • A suite of diagnostics • High rep rate (~Hz) is not essential at this stage • Adding a XFEL on top of this type of laser facility would help a lot to understand physics at the micron scale

	Energy	ranges: good/still possible/not working	1-10 kJ laser would be great
		threshold for new physics	hundreds of kJ should be enough; aiming for a MJ call facility is a safe bet
		role for scaling	important
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	Single-shot experiments are already meaningful but of cause high rep. rate (~Hz) would be great to optimize/test/investigate different parameters
		experiment over a long time (accumulation): stability important	important
		sufficient beamtime available at presently operational infrastructures?	Not really mentioned
	Pulse duration	ranges: good/still possible/not working	>10 ns
		threshold for new physics	Not really mentioned
		variability/pulse shaping necessary	Pulse shaping with high fidelity is necessary
		role of spectral content	Not really mentioned (High bandwidth to decrease instabilities ?)
	Temporal contrast	ranges: good/still possible/not working	Not really mentioned
		best possible or controlled?	Not really mentioned
	Beam quality	which aspects are important?	Testing different beam profiles / phase plates would be good
		importance of peak intensity?	
		Gauss - good enough? Other shapes - better?	

Speaker: F. Wasser
HEHRR laser for IFE

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Driver for IFE: Compression lasers and lasers to drive secondary proton sources as fast ignitor. - What physics questions can be addressed with the methods? • Optimization of the major breakthrough which was done at NIF, but with another setup: Direct drive, Proton Fast ignition Fusion.
Limitations	- Laser parameter range available and which are the limitations imposed by these? • Currently available mainly several hundred joule lasers, MJ lasers not usable • Limitations are clearly energy, but also bandwidth of the compression laser which may help mitigate LPI

Future	- What laser parameters would be desirable and would these make new physics accessible? • Compression laser o Energy: 2 MJ with 1-5 kJ per beam o Temporally shaped, pre pulse with ramp up. ~25 ns o Focal spot 1 mm o Wavelength 527 nm (SHG of Nd:glass) ▪ However LPI is more critical at 527 nm , more bandwidth to mitigate this ▪ Bandwidth 3.5 % for the scheme should be sufficient • Ignition laser o 200 kJ short pulse laser, per beam 1-5 kJ, 3-10ps, < 100µm focal spot o Conversion from laser to proton from 10-15% must be demonstrated ▪ Tunable (delay and duration) Multi-pulse capabilities may be useful. Tunable in temporal contrast		
	Energy	ranges: good/still possible/not working	1-5 kJ per beam feasible without addressing the other requirements
		threshold for new physics	Total energy: 2 MJ Insights might also be given by lower energy systems
		role for scaling	important
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	TO show fusion, only few shots necessary. For power plant stable shot sequences must be achieved
		experiment over a long time (accumulation): stability important	Stability highly important
		sufficient beamtime available at presently operational infrastructures?	no
	Pulse duration	ranges: good/still possible/not working	Good for long pulse, probably still possible for short pulse
		threshold for new physics	No threshold
		variability/pulse shaping necessary	yes
		role of spectral content	Important for compression laser. Large relative bandwidth (3,5%) and at 527 nm
	Temporal contrast	ranges: good/still possible/not working	Range not defined
		best possible or controlled?	Must be tunable to find optimum contrast for the goal

	Beam quality	which aspects are important?	Not directly specified. Probably uniformity (spot size <100µm for short pulse and around 1mm for compression pulse)
		importance of peak intensity?	Not mentioned
		Gauss - good enough? Other shapes - better?	uniform

2.2.8 HEHRR lasers for laboratory astrophysics

Bringing astrophysics into the laboratory

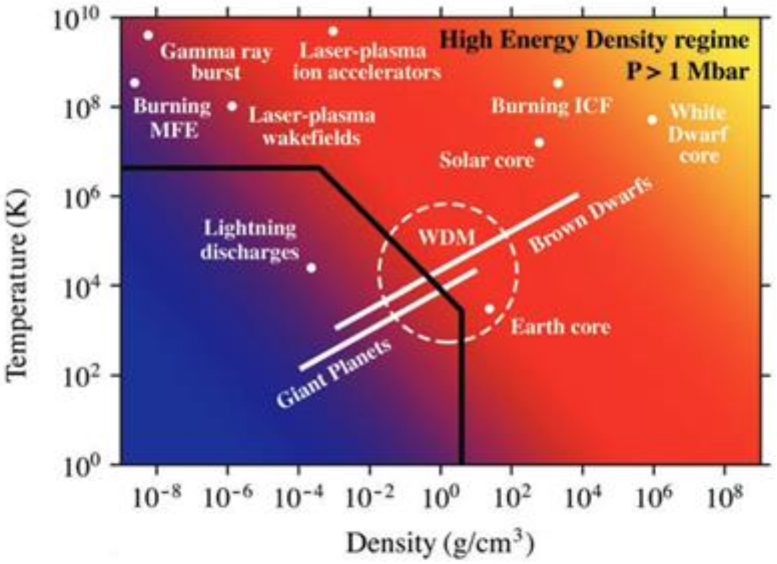

Figure 8: astrophysics-relevant areas in the HED diagram. [source: NASEM Report (2020)]

HED physics has a significant overlap with states of matter as they can be found in astrophysical objects and processes. Collisionless shocks play an important role in many phenomena, such as the Earth's bow shock, relativistic jets, supernova remnants, galaxy clusters. Their behaviour in terms of e.g. hydrodynamical instabilities and shock microphysics is not yet fully understood, therefore recreating these states in laboratory conditions can provide valuable insight. The astrophysical scales of size, pressure, density and time can be scaled to the laboratory size by applying a hydrodynamic description, which then allows to study these kinds of systems in laboratory conditions, using HEHRR lasers for the creation and diagnostics. High-energy laser facilities (i.e. kJ-class systems with ns pulse duration) can access the non-relativistic collisionless shock regime, while high-intensity lasers (PW peak power, 100 fs pulse duration) open up the relativistic regime. For the diagnostics, laser-driven diagnostics are used (proton radiography, Thomson scattering) and the combination with an XFEL significantly benefits the achievable spatial (sub-µm) and temporal (sub-ps) resolution.

Recent experiments at the high-energy laser facilities OMEGA and NIF have resolved the questions of magnetic-field amplification, electron heating, and nonthermal acceleration, while in the relativistic regime the density structure of the instability-induced filamentation has been successfully imaged.

Laser requirements for laboratory astrophysics studies

The lasers used as drivers for exploring the non-relativistic collisionless shock regime require high energy (100s J to > 1 kJ), a large, smooth focal spot (1 mm, with phase plate), and long time scales (**ns pulse durations**). For improved coupling from the laser into the plasma, frequency conversion

(2ω or 3ω) would be beneficial. In terms of repetition rate, 1 Hz would allow for systematic studies with high shot statistics. However, since currently the required laser parameters are only available at the few-shot-per-day level, already an increase to **1 shot/few minutes and a pulse energy of 100 J at 2ω** would allow for a paradigm change in the field. For diagnostics and/or accessing the relativistic regime an ultra-intense laser is necessary with the desired parameters of **1 PW peak power, < 100 fs pulse duration**, i.e. 100 J pulse energy, which can be focussed to an **intensity of > 10^{19} W/cm^2**.

Speaker: F. Fiuza
HEHRR laser for astrophysics

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Driver of collisionless or relativistic shocks - What physics questions can be addressed with the methods? • Investigation of collisionless shocks: important for earths bow shock, relativistic jets, supernova remnants, galaxy clusters ○ Energy partition is a fundamental open question in these shocks ○ Magnetic field amplification ▪ No consensus yet on the dominant microphysical mechanisms that amplify the magnetic field at different scales
Limitations	- Laser parameter range available and which are the limitations imposed by these? • MJ at NIF, multi kJ at MEC • Repetition rate its typically very low • combine high power optical laser with x-ray laser would be nice
Future	- What laser parameters would be desirable and would these make new physics accessible? • Laser parameters non relativistic shocks ○ Energy > kJ (better > MJ) ○ Duration > 1 ns ○ Intensity 10^{14}-10^{16} ○ Rep. rate 0.01 Hz ○ Temporal contrast controlled ○ Beam quality controlled ○ More pulse options would be beneficial • Laser parameters relativistic shocks ○ Energy > 100 J (better > kJ) ○ Duration > 100 fs (>1ps) ○ Intensity 10^{19} ○ Rep. rate 1-100 Hz ○ Temporal contrast controlled ○ Beam quality controlled ○ More pulse options would be beneficial

	Energy	ranges: good/still possible/not working	Up to some kJ probably feasible at long pulse, but challenging for short pulse
		threshold for new physics	The more the better
		role for scaling	important
	Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	Demanded rep. rate currently not or only barely feasible
		experiment over a long time (accumulation): stability important	Not specifically mentioned
		sufficient beamtime available at presently operational infrastructures?	Only few facilities which can deliver such energies
	Pulse duration	ranges: good/still possible/not working	good
		threshold for new physics	Not mentioned
		variability/pulse shaping necessary	Not specifically mentioned. Maybe meant by “temporal contrast” in long pulse laser?
		role of spectral content	Not mentioned
	Temporal contrast	ranges: good/still possible/not working	No numbers specified
		best possible or controlled?	controllable
	Beam quality	which aspects are important?	
		importance of peak intensity?	Not mentioned, but short pulse around 10^{19}-10^{21} and ion pulse around 10^{14}-10^{16}
		Gauss - good enough? Other shapes - better?	Should be controllable

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Speaker: C. Kuranz
HEHRR laser for astrophysics

State-of-the-art	- What are high power lasers used for in the field (drivers, diagnostics)? • Most of the experiments have one driver laser and one for diagnostics - What physics questions can be addressed with the methods? • HED physics significant overlap with astrophysical systems • Experiments can complement observation and theory
Limitations	- Laser parameter range available and which are the limitations imposed by these? • Available at the moment: ○ SACLA: 500 TW, 1 Hz, 40 J, 1 ns ○ Eu-XFEL: 300 TW at 5 Hz and 100 J in 10 ns up to 10 Hz

	• What will be existing "soon" ○ Eu-XFEL plans for 700 J in 1 ns at 1 shot/min ○ MEC-U 200 J, 1 ns, 10 Hz (planning phase) • All single shot • There are many other laser facilities but few support long pulse and high rep rate, which are key for lab astro experiments
Future	- What laser parameters would be desirable and would these make new physics accessible? Great: • 1 kJ and 1 PW at 1 Hz, 1-mm phase plate, tunable 1-10 ns, 3omega Still good: • 100 J and 1 PW at 1 shot/min, 1-mm phase plate, 1ns square pulse, 2w

Energy	ranges: good/still possible/not working	Good: 1 kJ Still ok: 100 J
	threshold for new physics	Not mentioned
	role for scaling	Not mentioned
Repetition rate	single-shot experiments: how many shots are necessary for meaningful experiment?	1shot/min – 1Hz
	experiment over a long time (accumulation): stability important	Not mentioned
	sufficient beamtime available at presently operational infrastructures?	Not mentioned
Pulse duration	ranges: good/still possible/not working	Good: tunable 1-10ns Still ok: 1ns square pulse
	threshold for new physics	
	variability/pulse shaping necessary	
	role of spectral content	
Temporal contrast	ranges: good/still possible/not working	Not mentioned
	best possible or controlled?	Not mentioned
Beam quality	which aspects are important?	1 mm phase plate
	importance of peak intensity?	
	Gauss - good enough? Other shapes - better?	

2.3 Summary table for laser parameters

The laser requirements for the different fields based on the end-user workshop presentations are summarized in Table 2.

	WDM/Comp.	**QED/Nuclear**	**B- Field**	**Bio.**	**IFE**	**Lab astro**
Energy, pulse	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 (thee 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 2: summary of all laser parameter requirements

In the discussion following the contributions several additional points were raised, which are not represented in Table 2, but are nevertheless crucial from the application point of view:

- Diagnostics of the laser parameters, especially on-shot are crucial. For comparison with theoretical predictions, knowledge of the pulse energy is one of the most critical parameters.
- Automated stabilization and control of the laser parameters is necessary, especially when repetition rates in the Hz-range are reached. Here the possibility of applying AI in the control loops was discussed.
- Temporal pulse shaping capabilities are also required in many cases.
- As an additional laser architecture aspect, single or multi-beam schemes should be considered.

3 Conclusion and Outlook

Finding 1

Laser pulses with kJ or even several kJ of energy would allow to access new ranges of physical phenomena in the fields of warm-dense-matter research, dynamic compression of materials, laboratory astrophysics, magnetic-field generation and inertial fusion energy. In addition to the highest energies reached, key points are the on-shot diagnostics, to provide a good knowledge of the delivered energy in the focal spot, and the stability of the energy value.

For medical applications, high field QED and nuclear photonics, it is the laser-pulse intensity that governs the interaction. Here somewhat lower pulse energies (100 J up to several 100s of Joules) are sufficient. Stability and reproducibility are especially important in these fields.

Finding 2

While currently it is possible to carry out meaningful experiments at a repetition rate as low as 1 shot per day on the highest-energy laser facilities, scaling this to 1 shot/few minutes would allow for scans to explore the parameter space within a time frame feasible for experiment facilities and work force. In some fields (e.g. warm-dense-matter research, dynamic compression of materials, laboratory astrophysics, magnetic-field generation) target handling and diagnostics would need to undergo significant development before higher repetition rates could be handled.

Again, medical applications, high field QED and to some extent nuclear photonics require repetition rates as high as possible (1-100 Hz) in order to reach the dose rates and statistics, respectively. The field of inertial fusion energy also relies on repetition rates in the 10 Hz-range, in order to provide the necessary power one the development stage is completed and the power-production phase starts.

Finding 3

Beam quality is also an important factor that needs to be taken into account for a number of applications. When short pulses (fs) are used, this aspect is more critical, since in the high-energy systems phase plates can be applied to ensure a smooth intensity distribution at the interaction.

Finding 4

With an increased energy towards the kilojoule, the precision of data will increase to the necessary level to perform physics-relevant and impactful studies. Experimental program at scaled-down energy already exist, which means that diagnostics and data acquisition and analysis methods are used in routine operation. This should ensure an efficient, swift and low-risk start, once new HEHRR lasers become operational, ensuring a fast return on investment for such facilities.

Summary

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 is that while the THRILL project will not be able to provide all fields with the next generation laser technology, the direction set out 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.

Figure 9: group picture of the workshop participants

4 Annexes

4.1 Annex 1 - minutes of the workshop round table discussion

Date: 25.10.23 16:30 Author: Stephan Neff

Participants: End users, THRILL members

Introduction

- Vincent Bagnoud (VB) opened the discussion by presenting a table with laser requirements which he had compiled based on the presentations from the end-users.

- The table lists the requirements for several kinds of experiments: Warm Dense Matter and compression experiments, QED and nuclear physics experiments, experiments with laser-generated B-fields, biological experiments, experiments related to inertial fusion energy research and experiments in the field of laboratory astrophysics.

- VB also pointed out that the requirements for the development of diagnostics and for additional laser beams to drive these diagnostics should be taken into account. Afterwards, the requirements of each type of experiment were discussed with the end users.

Warm Dense Matter (WDM)/Compression experiments/ICF and IFE

- D. Kraus (DK) stated that high energy ps pulses should also be included in the list of requirements, since in the future experiments studying isochoric heating with coupled laser – XFEL beams would require a short-pulse beam.

- VB asked about the repetition rate that would be required for the experiments in the field of WDM.

- T. Cowan (TC) stated that one should focus on realistic laser parameters that are achievable within the scope of the THRILL project. VB stated that shot rates of up to 1 shot/minute are realistic goals and that for the technology development to be relevant in the future, one must know what the real requirements of future experiments are.

- P. Audebert (PA) pointed out that the project is focusing on developing the capabilities of European research facilities.

- With respect to the maximum repetition rate, E. Brambrink (EB) pointed out that most experiments cannot make use of a shot rate that is higher than 1 shot/minute. Very few experiments require and can make use of a shot rate of 10 Hz. Once a laser shot rate reaches 1 shot/minute, it is usually no longer the limiting factor for an experiment.

- F. Wasser (FW) added that for Focused Energy, the 10 Hz shot rate is only a requirement for the final fusion power plant, but not for the science campaign in the near future. M. Roth (MR) added that Focused Energy will start the installation of their 10 Hz lasers in 2029 to demonstrate the necessary technology readiness level in their development plan, but that they will install the target delivery system for 10 Hz operation only later. In the meantime, 1 shot/minute or even 1 shot/5 minutes would already be a game changer compared to the current situation and would allow for many new experimental opportunities.

- DK added that for the complicated targets used in some of his experiments, a repetition rate in the Hz range is not feasible.

- MR pointed out that the bandwidth of the laser system should also be included in the table, since it significantly affects the design and since a sufficient bandwidth is needed for beam smoothing in compression experiments.

QED/Nuclear physics experiments

- E. Los (EL) pointed out that high peak intensities and a very good beam stability are important for high-field QED experiments.

- TC stated that for their vacuum birefringence experiments the beam energy and focusability would be most important and that the new laser system would be complimentary to the existing ReLAX laser system.

- P. Thirolf (PT) stated that for nuclear physics experiments, a beam energy of at least 100 J is necessary (at 10-20 fs pulse length). In order to achieve sufficient statistics in the experiments, a repetition rate higher than 1 shot/minute is also necessary.

- PA and TC stated that the first step of experiments should be to demonstrate RPA and that for these experiments ultra-high repetition rates are not necessary.

- VB stated that while beam quality and bandwidth are important to reach the highest intensities, work on the frontend is not part of the scope of THRILL and therefore THRILL will focus its activities on amplifier development.

B-field generation experiments

- For experiments using laser-generated magnetic fields, two beams are needed.

- One setup would combine XFEL with a long-pulse beam and a beam from a fs laser.

- Another experiments would use two high-energy long-pulse beams.

- For generating the magnetic fields, a 1ω beam would be preferable. However, VB commented that working at 1ω requires a strong isolation scheme to protect the laser from backscattered light.

Biological experiments

- TC noted that biological experiments are currently not planned for HiBEF, but these experiments are carried out at dedicated laser systems such as the Draco laser. For carrying out experiments studying the FLASH treatment scheme, higher energies than available at Draco are probably needed. For these studies, a ps-PW laser system could complement the existing ReLAX laser.

- For biological experiments with electrons, the needed beam energy is not very high (hundreds of mJ), but a very high shot rate (100 Hz) and very good shot-to-shot beam stability is needed.

Laboratory astrophysics

- No participants from the Laboratory Astrophysics section took part in the discussion.

- VB noted that the requirements for these experiments are very similar to those of other topics, for example to those for WDM experiments.

Conclusions

- VB noted that another important issue is the need for better diagnostics of the laser beam parameters.

- TC supported this by stating that a shot-to-shot diagnostic is very important for strong-field experiments.

- VB asked how important the predictability of the shot parameters is and if the role of AI for such diagnostics should be investigated as part of the THRILL project.

- EB added that there is a huge demand from the user side for pulse shaping capabilities and for predictable laser parameters. For experiments with a 1 Hz shot rate, an automatic processing and adjustment of the laser parameter is needed, as well as a feedback for an automated stabilization of the beam.

- DK agreed that an automated setup to select pulse shapes would be very helpful.

- It was commented that using multiple beams might make pulse shaping easier.

- PA started the discussion about the priorities for the THRILL project. The participants agreed that the development work should take already existing facilities into account and focus on the setups for XFEL and FAIR, while trying to find synergies along the way.

- TC added that an important design decision will be whether multiple combined beams or single high-power beams will be used.

- MR added that developing the capability to develop large-scale optics in Europe is also an important aspect. For example, obtaining large-scale gratings is currently a bottleneck for high-power laser systems.