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WORKSHOP REPORT

Tackling Some Inertial Fusion Energy Challenges at the European XFEL

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Abstract

The worldwide interest in Inertial Fusion Energy (IFE) has increased significantly since the first laboratory demonstration of ignition and burn at the National Ignition Facility (NIF). Both public research institutions and private companies now substantially invest into research and technology development for IFE. The German government has recently initiated the ambitious funding programme “Fusion 2040”, which includes the goal to establish German hubs connecting academia, research institutions, and industry for IFE research and development as soon as possible. The High Energy Density – Helmholtz International Beamline for Extreme Fields (HED-HIBEF) activities at European XFEL would be a natural basis for such a hub, e.g. by installing a new dedicated IFE-Research Instrument (IFE-RI) at the facility and building on its international community.

This workshop aimed at a discussion of the role XFELs could play towards an IFE power plant, identification of IFE-relevant activities that could be pursued at the existing HED-HIBEF instrument, and flagship experiments with a future IFE-RI, ideally providing multi-kJ, multi-beam long pulse and short pulse drive lasers.

The topics discussed included:

- XFEL-based diagnostics of IFE target physics: Ablator and fuel equation-of-state (EOS), microphysics and transport properties, hydro instabilities, intense laser-matter interaction for shock and fast ignition, etc.
- Microscopic X-ray imaging and diffraction of dynamic radiation damage cascades of fusion reactor walls in strong radiation environments, including the lifetime assessment of plasma-facing materials
- XFEL-based diagnostics of IFE plasmas compatible with sub-scale and full-scale IFE facilities (i.e. with high repetition rate and extreme radiation environments)
- Laser technology required for IFE-RI

- Theory and simulation developments required to support an IFE programme at European XFEL.
- Setting up a new partner consortium for IFE research at European XFEL.

We invited both the IFE community and the broader HED community around European XFEL to convene for this workshop at our headquarters in Schenefeld, Germany on 11–12 June 2024. We had more than 100 total participants, 40 of whom joined by Zoom.

Figure 1: *Onsite participants of the workshop in June 2024*

Contents

1 First day – 11 June 2024

The Chair of the European XFEL Management Board, **Prof. Dr. Thomas Feurer**, delivered the opening speech and welcomed basic research for inertial fusion energy (IFE) as a new research direction at European XFEL.

1.1 Opening session

1.1.1 Welcome by Armin Haase, BMBF

Dr. Armin Haase (German Ministry for Education and Research, BMBF) pointed out that BMBF funding is no longer restricted to magnetic confinement fusion but now also covers laser fusion approaches. In the view of the BMBF, however, laser fusion is still considered a step behind magnetic confinement fusion. The European XFEL is a top-class facility, and BMBF welcomes the initiative of European XFEL and is curious to see how the facility can contribute with science and community building to the German fusion ecosystem.

1.1.2 Welcome by organizing committee

In the first session, chaired by **Thomas Cowan**, European XFEL Scientific Director **Sakura Pascarelli** introduced and welcomed the local organizers and the international programme committee, and gave an overview of the workshop programme. She reported that, recently, European XFEL responded to the BMBF call for Fusion 2040, with the aim to develop a science hub and identify which IFE challenges could be addressed using the European XFEL facility. The company plans to establish a dedicated IFE instrument in different stages. Short-term, it will offer IFE experiments using the existing experiment platform, in particular at the HED-HIBEF instrument. Mid-term, it can upgrade the capabilities in the existing experiment hall. Long-term (>8 yrs.), the company envisions a dedicated IFE building housing a multi-beam facility. The company will also strive to build an international partner consortium.

Justin Wark (Univ. Oxford) reminded everyone of the successful foundation of the HIBEF user consortium. HIBEF constitutes more than 80 institutions and is considered a huge success. Coming together internationally has revolutionized the way HED science is done, and the same collaborative spirit could work again for fusion energy science. The UK's contribution and expertise to IFE is dominantly coming through researchers and experiment infrastructure at Imperial College, the Universities of Oxford and York, Queens University Belfast, and the UK Research and Innovation (UKRI) Central Laser Facility (CLF). The UK has a strong track record in inertial fusion, and the number of former UK researchers working on National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) is large. The UK has its own fusion consortium as well as start-ups like First Light Fusion. Moreover, research grants (prosperity partnership) between private and academia exist. As proven via the DIPOLE laser, the UK has very strong expertise in laser technology.

Paul Loubeyre spoke on behalf of the European XFEL Scientific Advisory Committee (SAC), the HED Peer Review Panel (PRP), and the French high-pressure scientific community. The positive conclusion of the recent HED-HIBEF five-year review is that the remarkable staffing of this instrument has led to a world-leading position in HED science and provides unmatched capabilities, with the RELAX and DiPOLE lasers, a cryo-jet target delivery, diamond anvil cell (DAC) platform, and unique X-ray properties, such as photon energies up to 30 keV and very bright, MHz pulse trains with 4.5 MHz repetition rate. The SAC recommended the organization of this workshop, which was realized with an excellent programme on short notice. A strategic decision has to be made to pursue fusion science at European XFEL.

1.2 Scientific talks

1.2.1 New lights on fusion – Micro to macro physics (Collins)

As a first invited speaker, **Rip Collins (University of Rochester**) introduced the three major US facilities: the National Ignition Facility (NIF), OMEGA, and the Z-Facility at Sandia. Their primary approaches are laser indirect drive, direct drive, and magnetic direct drive, respectively. He went through a deuterium–tritium (DT) capsule simulation with plastic (CH) ablator and the history of target gain at NIF reaching the DOE requirements for ignition in 2022 as well as the hotspot gain improvements achieved at OMEGA. Rip outlined the potential opportunities of combining an XFEL with these platforms, as this holds strong potential to unravel longstanding questions in the microphysics models as well as beginning to enable understand the implosions in flight.

It is e.g. currently not fully understood how the burn waves propagate into the fuel after ignition. He showed the currently possible neutron imaging capabilities and emphasized that X-ray phase contrast imaging could be more precise.

The so-called microphysical model requires inputs, such as opacity, equation-of-state (EOS), transport parameters, kinetics, and nuclear information, and can then be used with Bayesian and AI methods to model experiment data.

The conversion of blue laser light into X-rays, the laser–plasma interaction and opacity, and heat transport and radiation transport in hohlraums are complex. The gold in a hohlraum is in a highly non-equilibrium state with keV electrons. Their radiation spectrum is very complex, has a non-Planckian tail, and it is crucial to understand pre-heat and late-time dynamics of the shell. X-ray heating of the capsule and creation of a well-tuned ablation is critical and a prerequisite for uniform implosion. Moreover, CH capsules are often doped with higher-Z materials like zinc, and any change in opacity can affect the implosion.

Regarding ablator EOS, Rip stressed the importance of XFEL-based results of Frost, Kraus et al. on CH phase separation into diamond and hydrogen and the general complexity of high-pressure chemistry at elevated temperatures.

Rip emphasized that sharp X-ray phase contrast imaging of shock waves requires ultrashort X-ray pulses. Results of such experiments at LCLS on Kapton showed the development of substantial structures on the micrometre scale behind the shock front, which is currently not understood.

The primary high-yield ablator at NIF is now nanocrystalline diamond. It is not understood how the nanocrystalline Hugoniot is offset with respect to single crystal diamond. Ideas point towards voids in the diamond ablator that could be imaged by X-rays.

In warm dense matter (WDM), the atomic (Rydberg), thermal, Fermi, Coulomb plasmon energy are all on a comparable level. As a consequence, long-range correlations play an unexpected role in the internal energy. Potentially, a plasma wave (plasmon) could cause an offset in compressibility of deuterium, and this could be verified with an XFEL.

Thermal conductivity is very important to capsule stability—an increase of a factor 3 changes the peak-valley density modulations by a factor 4. Spatial resolution beyond current capabilities at NIF and OMEGA is required to observe this, and XFELs might be the solution.

At stagnation to hot spot, the energy is transferred to the ions, then to electrons that radiate. Measurements of stopping power are equally important as radiation transport. At OMEGA, implosions of Cr-buried layers allow to study atomic states and observe the shift of absorption lines. Depending on the free electron concentration, they affect and change inner orbital energies (20 eV shifts). Currently, the X-rays are self-emitted only during stagnation, but XFELs could probe the plasma all the way before and unwrap these atomic states. Once better understood, this could be used to tune the X-ray opacity of the shell.

A key missing link is the investigation of all the reverberating shocks with an X-ray probe instead of just Velocity Interferometer System for Any Reflector

(VISAR), as this information is used to time and tune the shocks to obtain a convergent ablator.

Also, currently, there is a lack of resolution regarding the shape of the capsule. Better than 1 µm resolution would reveal a great deal of additional information. Photon energies >20 keV are required because of the strong plasma background radiation as well as sub-ps temporal duration. Currently, laser-based back lighters last 20 ps or longer. Nevertheless, perturbations were observed, but researchers are unable to make out their seed formation during flight, as this would require nm resolution and sub-ps pulses.

In conclusion, there exists a big opportunity to build a big laser next to an already operating XFEL. Rip Collins pointed out several examples where XFELs can help with ultrafast X-ray imaging and resonant ionization state probing. At OMEGA, the requirement for an improved X-ray source are also evident, and plans exist to build an inverse Compton source. For European XFEL, the minimum energy of a drive laser to address the open questions is 1.5 kJ, which could answer a few first questions regarding the microphysics. Stepping up to converging-geometry experiments, which Rip Collins thinks the community should pursue, requires a 200–300 kJ laser in the blue with a broad bandwidth.

1.2.2 Advancing fusion energy physics with XFELs (Vinko)

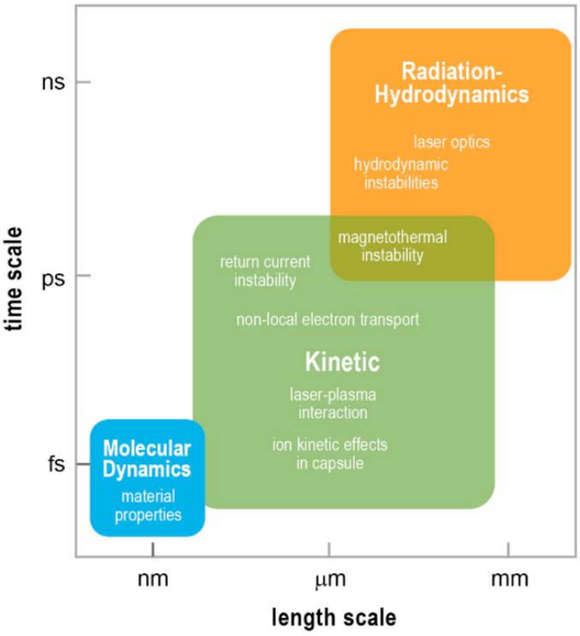
Sam Vinko from the **University of Oxford** talked about advancing fusion energy physics with XFELs. He stressed the lack of experiment facilities that are able to achieve IFE conditions. This minimum are pressures of 10s of Mbar at temperatures of 30–100+ eV, at densities of 10–100+ g cm^{-3}. Furthermore, options for spherical compression and potentially magnetic fields are necessary. This would require laser drivers of IFE-relevant parameters, in the UV, with 10–100 kJ pulse energy and multi-THz bandwidths, and a minimum of 8+2 beams.

Such a laser needs to be coupled to an already existing XFEL. Sam also mentioned the need for education and training of a community as well as building expertise outside of defence labs. Access (time, capacity) at non-defence labs would open up much more for IFE research in his opinion. Sam finally highlighted several IFE reports by the UK and the US supporting coupling a large laser to XFELs.

Besides target physics and ignition, achieving precision control over targets and drivers is important. XFELs can study compression hydrodynamics, instabilities, transport (heat, viscous, particle), and mix. He highlighted fusion power plant integrated systems as well as material and damage studies. Besides being a better back lighter for X-ray phase contrast imaging (XPCI), XFELs offers new diagnostics (different spectroscopy methods, two colour-mode, MHz, etc.), and high repetition rate.

Sam reminded us that Artificial Intelligence (AI) and Machine Learning (ML) can only be applied to a large dataset. Sam presented an example in which an actionable model (which does not include the physics) was used to guide the plasma in magnetic confinement fusion (MCF) via a fast feedback loop. This suggests that, even without a complete understanding of the physics, we can still progress if high repetition rate data would become available. In his view, this will be a qualitative change, not just a quantitative change.

Figure 2: *Timescales and length scales in fusion energy research (Vinko)*



1.2.3 HiPER+ initiative

Sebastien Le Pape (**LULI**) spoke on behalf of the European HiPER+ initiative group. Sebastien reminded us that the original HiPER proposal was an IFE ESFRI roadmap project. In 2010, it was decided to focus on shock ignition, and finally it was discontinued. After the NIF results were made public, the community aimed to resurrect the project through HiPER+. A proposal for updated design studies for a European IFE facility is currently under review by the European Union.

They propose to work on lasers, targetry, high-repetition-rate diagnostics, and fusion reactors. Sebastien explained that direct drive is promising for achieving high gain. One way to limit instability growth in direct drive is to reduce the implosion velocity. This can be achieved by separating the compression and ignition phase. The latter can be achieved by so-called "fast" ignition (past: electrons, now: proton) or by shock ignition.

Thicker and more massive targets at lower implosion speeds of up to 240 km/s are intrinsically more resistant to hydrodynamic instability growth. Then, a final laser spike launches a strong converging shock (> 300 Mbar at ablation front). Preliminary experiments for this concept were done at OMEGA and NIF.

After this conceptual overview, Sebastien focused on open questions:

Laser-plasma instabilities: In order to launch a 300 Mbar shock, you need a laser intensity of $I_L = 5$ PW/cm^2, which is equivalent to 200–300 TW laser power. It is not clear how this pulse will couple to a pre-compressed capsule. Basic studies can be in made in planar geometry and may not require an XFEL.

Hydrodynamic instabilities: Particularly in foam targets, hydrodynamic instabilities arise from hot electrons, magnetic field effects, and engineering imperfections. Here, imaging experiments at XFELs have shown very good spatial resolution. Preliminary experiments with the existing DiPOLE laser at XFELs with 15–25 J, 4 ns pulses could be done now to study the impact of laser bandwidth and pulse shape on instabilities.

New target designs for high repetition rate need to be developed. EOS studies on (wetted) foams and other porous media require many experiments, which then allow benchmarking of predictions. Kinetic simulations of homogenization time of porous materials require imaging at XFELs for benchmarking.

Heat transport in underdense foams (for thermal smoothing/homogenization of the laser imprint) is an important issue but requires kJ energies. The general requirements for an XFEL probe are unclear; however, the plasma characterization can be done by X-ray Thomson scattering.

1.3 Talks by fusion startup companies – I

1.3.1 HB11 Energy, Australia

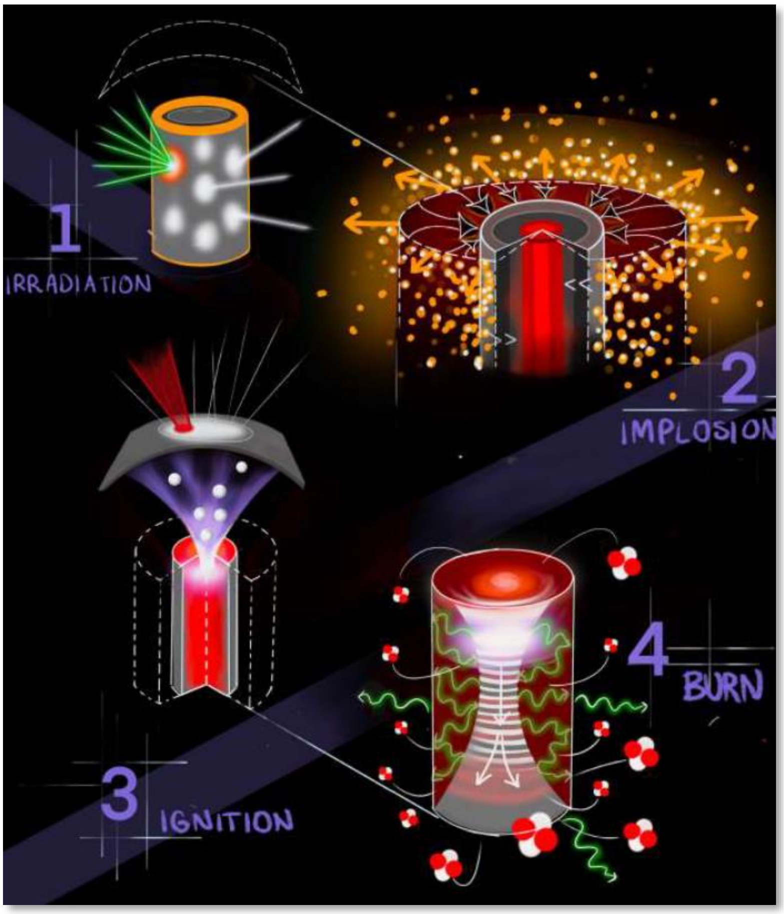
Sergey Pikuz (**HB11 Energy**) spoke about proton fast ignition of boron-11 fuel. This is the approach of the company HB11 Energy to achieve commercially sustainable fusion energy. Sergey explained that the pB reactivity is low but scales with fuel density, which calls for pre-compression. The p-^{11}B fusion energy yield is only three times higher than the energy needed to heat the fuel, so a large fuel mass is needed. Also, pB fusion requires very high temperatures of 200+ keV, which is not achievable via hydrodynamic compression alone but requires proton fast ignition. In their concept, laser-generated protons will be guided to the fuel by a magnetic lens.

A plant design with a separate proton acceleration stage on top and a compression stage on the bottom will yield 3 GW thermal and 1.2 GM electric power, and couple 0.9 GW to the grid. As a wall, HB11 considers a heavy material liquid blanket.

Sergey presented a techno-economical study of targets and lasers for the proposed power plant, based on mass production and consequently falling costs. An anticipated low cost of less than $1 per target seems favourable for pB targets over DT fuel designs.

To pave the way, XFELs can resolve the ionization dynamics in underdense aerogels and thin films. Moreover, the self-induced magnetic fields for proton guiding could be studied. Precise EOS of shocked HB materials as well as ablator materials (and instabilities) can be studied, and fuel burn can be studied with X-ray pumping and probing.

Figure 3: *Stages and times of proton-born fusion by HB11 Energy*



1.4 Talks by large national labs

1.4.1 Fusion programme at the National Ignition Facility

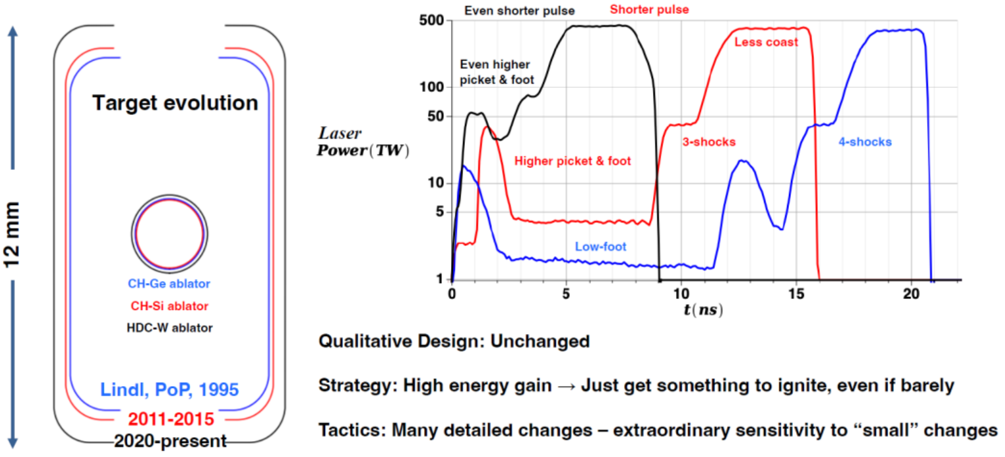
Omar Hurricane (**LLNL**) talked on behalf of the ICF indirect drive collaboration. He explained that it took a decade to master the instability control of the implosions, symmetry control, sufficient energy coupling, and target design.

The ICF implosion laser drive starts with a “foot” or picket to set the entropy. Peak power and coast time (laser off) are key to achieving efficient energy delivery to the fuel. The NIF hohlraums are made from gold or uranium. The radiation temperature in the hohlraum generates the ablation pressure, which scales with a high power (2.5–3.5) of the radiation temperature.

Omar went over the improvements during the last 20 years, since Lindl’s publication. The general tactics changed a lot, including many detailed changes that have large non-linear effects on the implosion. The hohlraum and capsule became 20% larger, while the laser parameters went to shorter durations. The ablator changed from CH to CH-Ge/Si to Diamond. The path to a working implosion explores a very large range of thermodynamic conditions (14 K to 14 keV temperatures, and up to 600 Gbar pressures).

Regarding future studies, Omar said that, without appropriate long-pulse multi-kJ lasers, XFEL studies are limited to effects of the ablator structure. These include micro-, nano-, and inner-surface defects of the capsule that cause mixing of higher-Z material into the core, which costs energy and can lead to failure to ignite. With larger lasers, a lot of insight can be gained at the 10 Mbar level.

Figure 4: *Today’s target design on the NIF was built upon a 10+ year evolutionary exploration of how to manage all the technical challenges (Hurricane)*



Qualitative Design: Unchanged

Strategy: High energy gain → Just get something to ignite, even if barely

Tactics: Many detailed changes – extraordinary sensitivity to “small” changes

Omar stressed that it is not understood why ρR values above 0.6 do not lead to more gain. This limits the fraction of burned DT fuel, which is 6.8% at NIF; however, IFE studies usually assume 33% in their power plant concepts.

LLNL and NIF have collaborated with Argonne National Laboratory (ALS) DCS (laser shock, DAC, gas gun), done ablator X-ray tomography at LBNL (ALS), and tested X-ray HCMOS detectors at LCLS.

To summarize, Omar stressed that the main problems were asymmetry and mixing. IFE needs higher gain, higher compression, higher ρR, and cheaper yet high-quality targets.

1.4.2 MEC upgrade project at the LCLS

Alan Fry (SLAC, LCLS) talked about the Matter in Extreme Conditions (MEC) instrument and the MEC upgrade plans at LCLS. He explained that there is a US Department of Energy (DOE) priority for Inertial Fusion Energy across many US labs. Fusion experts were added to the LCLS PRP to ensure qualified reviews. The current MEC upgrade (MEC-U) project is community-driven, and its evolution was based on the success of the MEC instrument. The project received input from a user advisory and facility advisory committee, and received very strong support from the FESAC committee review (initiated by the DOE Office of Science).

In detail, the envisioned science cases for MEC-U are relativistic plasmas, nonlinear optics in plasmas, HED hydrodynamics, magnetized HED plasma physics, warm dense matter, and planetary physics. From these, four first “flagship” experiments were selected: relativistic laser plasma, ion stopping power, (de)mixing in WDM, and planetary geochemical cycles. The MEC-U design requirements are based on these flagship experiments.

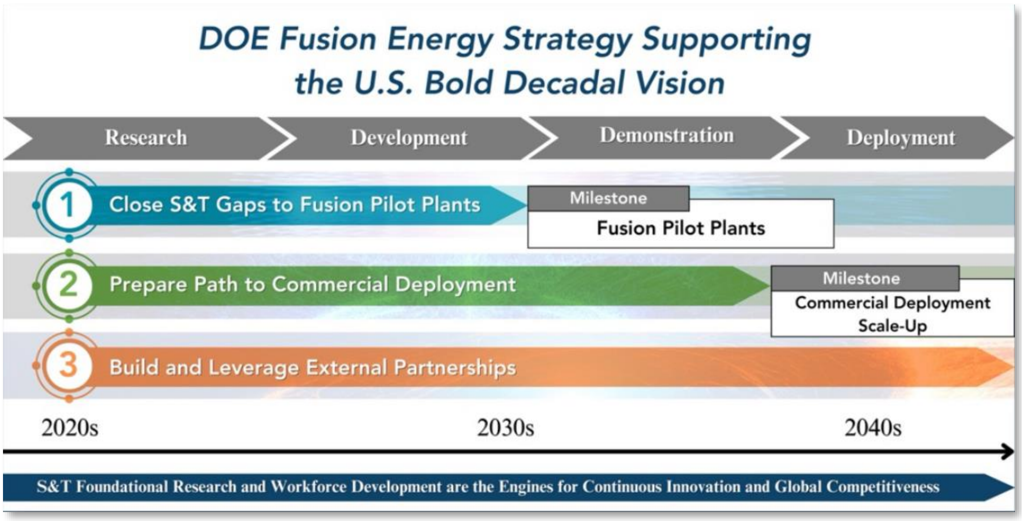
The MEC-U will host a petawatt and high-energy laser next to a spherical chamber. There will also be a secondary laser-only target area. The first laser is a high repetition-rate 10 Hz laser with 150 fs pulse duration and 150 J pulse energy, with a possibility to produce also a 200 J nanosecond beam at 2w. The second laser is a “shot per minute”-class 1 kJ shock driver with 3–30 ns shaped pulses.

Related to fusion, they plan to study the microphysics of wetted foams as proposed mass-produced targets, ion fast ignition schemes, and the phase diagram of diamond along the melt curve. Further research plans comprise radiation damage cascades (MFE relevant), H-He demixing in dense plasmas, and AI-driven high-repetition-rate science.

1.4.3 RISE hub in the US

Siegfried H. Glenzer (Stanford University, SLAC) focused on the task of how X-ray–based methods will pave the way toward fusion energy. He works on validating basic plasma science, extreme conditions, fusion material science, and inertial fusion science. Siegfried explained that the US DOE has published their US bold decadal vision, according to which the US will have fusion on the grid in the mid-2030s. He introduced the audience to the Inertial Fusion Science and Technology (RISE) hub, with Carmen Menoni as director and Siegfried as deputy director. The collaborating universities in this hub are the University of Colorado, Texas A&M, the University of Illinois, and Cornell University. Also joining are US national labs and companies, such as Marvel Fusion (focusing on high rep rate and multi-PW) and XCIMER (delivering a 248 nm MJ, 10 Hz laser) for laser technology and General Atomics for targets.

***Figure 5:** Three pillars of the DOE fusion strategy, shown with aspirational timeline that is strongly dependent on the level of investments.*



Regarding the target design of foams and encapsulation, Siegfried is convinced that XFELs can contribute. The current NIF target designs are good for improving the gain, and the current NIF targets will not be suitable for a power plant anyway, as they are too complex: current targets need to sit for days to even out the ice layer in the capsule, a process called beta-layering. Fusion targets need to support a high level of repeatability. In a plant, they will be injected into a target chamber that will still be hot from the previous ignitions. Also, sensors need to track injected fuel.

General Atomics developed several types of foams, where the DT goes into the foam cavities (“wetting”). Impurities from unavoidable mixing of foam material and DT will require higher energies to ignite. Currently, they can produce one target per second. Foam engineering can be assisted with X-ray tomography.

At the Matter in Extreme Conditions (MEC) instrument at LCLS, a first proof-of-concept experiment did X-ray imaging of laser-compressed (non-wetted) foams. It was observed that instabilities are forming that distort the shock wave, which calls for further iterations and improvements.

Regarding an implosion facility at an XFEL, Siegfried stressed that pressures of 100 Mbar should be aimed for. Good candidates for targets from this facility could then be sent to the NIF for Gbar tests.

X-ray imaging and small angle X-ray scattering (SAXS) at XFELs (LCLS or European XFEL) promise down to few 10s of nm resolution in femtoseconds. A temporal sequence of pictures, which tells us the evolution in phase space, will help us understand the instabilities.

For fast ignition, the measurement of ion stopping power is necessary to understand how ion beams get deposited in the fuel. In an MEC experiment, 1 MeV laser-generated protons were stopped in a Si target, and this process was successfully imaged by X-rays. Moreover, relativistic laser experiments X-ray imaged hot electron streaming instabilities, merging, and shock wave formation.

Finally, Siegfried stressed that wetted foams are potentially not the only solution, as other designs (see talk by Hartmut Ruhl) based on solids containing fuel are another interesting candidate.

2 Second day – 12 June 2024

2.1 Update on German funding scheme

2.1.1 Update by VDI technology centre

On Wednesday morning, a representative of the **VDI technology centre**, which handles the application details of the Fusion 2040 call by the BMBF, provided details about the funding initiative. **Christian Flüchter** informed us that the entire call in theory has a volume of 100 million euros (M€) per year over a duration of 10 years, of which funding is approved at least for the next five years. As usual, it is unclear what happens after the next elections.

The VDI received 17 sketches for “young researcher groups”, distributed across all fusion-related research topics, with a total request for 52 M€. Between one and 10 groups will finally be funded, depending not only on their quality but also on available budget. A decision will be made in autumn 2024, and the groups could then start as early as December 2024; however, most would start January 2025. A preselection will be done through virtual pitch meetings with the research group proposers in the beginning of September, and about ⅔ of them will be invited for a defence in front of a review panel.

In the “base technology” part of the fusion call, there are two modules. Module A is especially aimed at cooperation with industry and exploitation, had a first deadline on 15 April 2024, and will have a second deadline on 31 August. Further details about Module A will be distributed via VDI’s website, no emails will be sent anymore because VDI is assuming that the relevant community was reached and is fully informed.

VDI received 34 proposals for the first Module A call across all major topics, with more than 60 companies participating, which VDI appreciates highly. 314 M€ are requested, which implies that only ⅓ of the proposals could be funded. Consequently, the August call budget will be severely lower than 50 M€ for Module A. It will also depend on the requests for Module B, which has the same 31 August deadline. A decision for the April call will be taken within the next weeks, and all partners will be informed in the beginning of July 2024.

Complementary to Module A, Module B of “base technologies” is especially interesting for the research community and for European XFEL, as it will fund instrumentation for academia. Simulations in general will not be funded unless simulations are used to design the infrastructure. The deadline is 31 August, and no second round is planned. It aims for upgrading existing infrastructure, measurements principles, devices, detectors, and sources. VDI would welcome a compact neutron source with high flux, but also other lasers and particle sources are in their focus. Buildings or clean rooms will not be funded, only equipment within a building. Only research organizations and universities are eligible to apply; companies can be funded only in rare cases (new device developed with university for example). Proposals have to have a research project, not only build-up of infrastructure. Finally, operation of the equipment beyond the funding period by BMBF has to be guaranteed.

2.2 Talks by fusion startup companies – II

2.2.1 Focused Energy, Germany/US

The next session of the workshop was dedicated to further presentations by fusion startup companies. **Pravesh Patel** of **Focused Energy** (Germany/US) presented their laser facility roadmap for IFE. For an IFE power plant, the current NIF gain of 2.4 needs to be increased to 100, which is proportional to the fraction of DT fuel that burns. At NIF, currently 5.2 MJ are generated from a 7% burn fraction. The maximum practical fraction is 30% (20 MJ yield), which is an increase of only factor 4; it could be pushed to factor 10 at the most. The remaining required factor 10 can be achieved either by igniting more mass with the same laser or by igniting the same mass with 1/10th of laser energy, both of which are very challenging. A second aspect is robustness, since the current demands on target quality are very high.

One scientific question that Focused Energy is currently investigating is how low-adiabat compression with low velocity in thick shell implosions are achievable. They also state that there is very little scientific data on shocked cryogenic DT-wetted foam as a baseline target. Another question is the laser coupling to the hohlraum that is filled with hot dilute plasma. It is unclear whether laser plasma instabilities (LPI) such as stimulated Raman scattering (SRS) or cross-beam energy transfer (CBET), which divert the laser intensity from the hohlraum and lead to asymmetric compression, can be suppressed using frequency-doubled or tripled beams, (2w and/or 3w), and whether high proton conversion efficiencies and tight focusing can be achieved. Finally, can the relevant pressure for shock ignition of pre-compressed fuel be reached?

De-risking strategies include studying the science of ignition: confidence is required to be able to extrapolate to full scale. On the technical side, IFE-relevant technologies, such as 10 Hz targets and lasers, and diagnostics are required as well as a certain flexibility in the range of schemes to study and an enhanced shot rate to navigate and map out the design space.

Prior to building of a fusion energy plant, Focused Energy plans to build a sub-scale implosion facility and work there on de-risking the science in a first phase. A shot every three minutes (100+ shots a day) on DT-wetted foams can be achieved with flashlamp-pumped lasers, which are cheaper than diode-pumped ones. A broad laser bandwidth is required for LPI suppression studies, and many beams for a fully symmetric geometry. A second phase at the same facility would aim for a major technology demonstration. This would require the addition of a cryogenic target injector and 6–8 10 Hz diode pumped beamlines with fast steering for target engagements and upgraded diagnostics to run testing sequences of implosions. Their facility costs about 600 M€, so the available BMBF funding will not suffice, and they are looking for public–private partnership

A final upscale (third phase) is planned to have a 50 kJ long pulse (3w) + 10 kJ short pulse (1w), and upgrade a shot / 3 min repetition rate to 10 Hz for a full-scale facility.

XFELs can contribute to fundamental physics, like studying new ablators. In Pravesh's view, as long as implosion studies at 10 Hz are not possible, it is not efficient to couple these studies to a high-repetition-rate XFELs.

2.2.2 Marvel Fusion, Germany

The next presentation was given jointly by **Hartmut Ruhl** and **Daniel Rivas** by **Marvel Fusion (Germany)**. Hartmut Ruhl outlined the strategy to avoid laser plasma instabilities by use of incoherent laser beams, e.g. by an array of ultrashort laser pulses, which naturally have a low coherence.

Then, Hartmut talked about cheaper non-cryogenic solid-state targets. Marvel Fusion researches fast ion generation from nano-acceleration, using these ions to drive an imploding tamper. The gain limit for these fuels is 250–300. Practically, such a nano-rod target is irradiated by a laser pulse with a high intensity of 10^{21} W/cm² where up to 30% laser coupling for ~50 nm rods occurs.

Daniel Rivas focused on a recent result from the ODIN project at the ELI-NP laser facility. Researchers from Marvel Fusion characterized their nano-accelerator, consisting of a 100 x 100 µm² array of 15 µm long wires of 70 nm diameter. The nano-wires are that long because volumetric interaction is important. During the ODIN tests, the laser performance was not optimal since it did not deliver sufficient energy into the focus spot, and the temporal contrast of the laser had to be improved by means of plasma mirrors because a good contrast is necessary, but it was not properly characterized. Nevertheless, they successfully accelerated ions and benchmarked the wire target against a flat surface. A Thomson parabola measured MeV ion spectra as a function of wire diameter, with the highest yield for wires with diameters between 100 to 160 nm.

Marvel Fusion proposes to use an XFEL to understand the dynamics inside the wires. This requires X-ray imaging with better than 100 nm resolution, shorter than 50 fs temporal resolution, and larger than 5 keV photon energy, which is already possible with European XFEL's current capabilities. First, laser coupling and ionization of a single rod can be studied with resonant X-ray energies, and then a volumetric study of many rods can follow (using

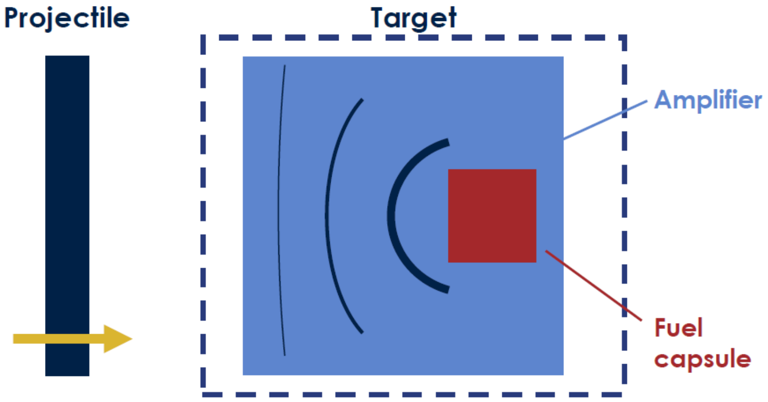
SAXS and emission spectroscopy). Future studies would focus on the energy deposition in fuels and materials, and energy scaling with the number of lasers. To achieve this, one would need up to three 100 J–class lasers.

2.2.3 First Light Fusion, UK

Francisco Suzuki-Vidal, the lead scientist for collaborative experiments at **First Light Fusion** (UK), introduced their fusion energy concept. Over a decade ago, they were a startup from Oxford University. First Light Fusion has received a completely private invest of 90 M€, and have headquarters and labs with 100 people near Oxford. Their scientific departments include experimental physics, pulsed power, computational science and engineering, target design, and power plants.

Francisco explained that First Light Fusion uses a flat projectile driver, which is low cost and transports a significant amount of energy at low power. They use in-house projectile drivers: gas guns and pulsed electromagnetic accelerators. The projectile hits a custom designed “amplifier” target, which drives convergent compression shock waves onto an embedded fuel. This process converts initial pressures of 80 GPa into 1.2 TPa and initial impact velocities of 6.5 km/s into 70 km/s into the fuel.

Figure 6: *First Light Fusion’s concept of a single-side projectile impacting a shock-amplifying medium (Suzuki-Vidal)*



First Light Fusion already collaborates with Sandia National Laboratories (US), Imperial College, Oxford and York (UK), and the ESRF (France), where they recorded a radiography movie of the impact. They also have funding schemes through the UK Engineering and Physical Sciences Research Council (EPSRC) to support scientific community-building through 11 Ph.D. students, 14 postdocs, and 40 summer interns. Scientifically, they study a range of density, temperature, and pressures from warm dense matter regimes to a burning plasma, including instabilities and mixing. They are currently planning to build a new gas gun capability at the ESRF though a private industrial partnership proposal.

Francisco explained that their company needs data on imaging with a minimum of 1 mm field of view and about 1 µm spatial resolution. A time resolution of 3 ns is required, as well as hard X-rays to penetrate high-Z and dense matter. With these capabilities, they propose to study the pressure release, including potential instabilities, into the fuel. Further, they will study the material properties of the fuel capsule.

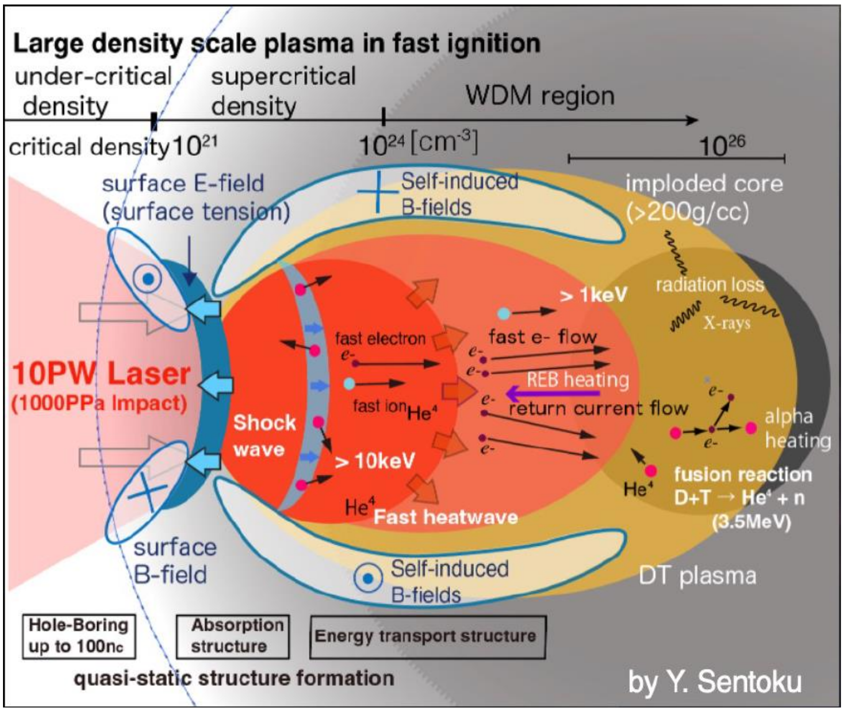
2.3 Scientific talks

2.3.1 Electron Fast Ignition and the FIREX-NEO project

Yasuhiko Sentuko (U Osaka) talked about fast electron ignition with picosecond petawatt laser light. The decades-old scheme of fast electron ignition does not work based on experiment results obtained using femtosecond duration lasers. At ILE, the FIREX-NEO project aims for numerical experiment optimization for fast ignition. They seek an implosion scheme with a 200 kJ long pulse laser, followed by heating by a 100 kJ – class picosecond laser, to achieve a target gain of 100, which translates to 30 MJ fusion output.

In Fast Ignition, only high density is necessary, no fast implosion, which is allowing for a solid ball design. In their proposal, a five-step 45 ns laser pulse compresses the core to more than 200 g/cm^{-3}. The ablator density profile is such that the critical density is 200 µm away from the core, usually, so laser in-coupling is challenging. However, picosecond Petawatt 200 J lasers pulse can hole-bore to the core in 10 ps. Particle-in-cell simulations using PICLS-2D with Coulomb collisions predict electron heating of the core to temperatures exceeding 10 keV, suggesting an efficient process exists if it has 10 ps time to develop. Yasuhiko treated the process as a heat wave, propagating with 8% the speed of light. It also accelerates deuterium and tritium ions, but the stopping power in the core is already to low due to the high core temperature.

Figure 7: *Concept of a PW laser drives “fast heatwave” and ignites core in 10ps, called the “Fast Heatwave Ignition” or FHWI (Sentoku).*



XFELs could reveal the solid ball implosion dynamics and the heating process. Yasuhiko proposed a picosecond kilojoule laser (1 PW per 1 ps, 1 kJ, 100 GPa, $I > 20^{21}$ W/cm^2, in 20 µm diameter), and, for a sub-scale facility, a 10 µm DT wire target can be studied. There will be a very strong magnetic field which could be diagnosed by XFELs too.

2.3.2 Academic landscape in Germany

Matt Zepf (Univ. Jena) spoke about the academic landscape in Germany. He started his talk with a review of laser fusion concepts. Most of these rely on DT fusion, which is scientifically validated. It requires a core temperature of 10 keV and a strong confinement. All other reactions are speculative, and alternative fuels at the same reaction rate need higher temperatures. The NIF concept with hot-spot ignition requires a burn wave for significant gain, which is limited in their concept, as the facility was not designed for gain scaling.

Simply increasing the laser energy and increasing the gain to 100 would release too much energy (GJ) in one shot, which would put too much strain into a power plant. Fast ignition (isochoric) separates compression and ignition but these heating concepts are scientifically not proven. Shock ignition is similar to fast ignition in the sense of separating these two processes, except that a single laser does both jobs by launching an igniting spark at the end of compression.

Figure 8: *German academic landscape for IFE (Zepf). XFEL here means the European XFEL and DESY.*

The German landscape involved in inertial fusion-relevant research consists of the University of Rostock, the European XFEL in Hamburg/Schenefeld, HZDR Dresden, HHU Düsseldorf, HI Jena, GSI and TU Darmstadt, and LMU Munich. Most of these laboratories are focusing on ultrashort lasers and related diagnostics. The European XFEL provides a high degree of precision that the community can use to diagnose potentially new target designs, which allows now insights. In this way, the European XFEL can bridge between theory and simulations, and short/long pulse laser science. Effort is needed to achieve a coordinated fusion program in Germany and Europe, and last but not least, future specialists require training.

2.3.3 Fusion opportunities at GSI and FAIR

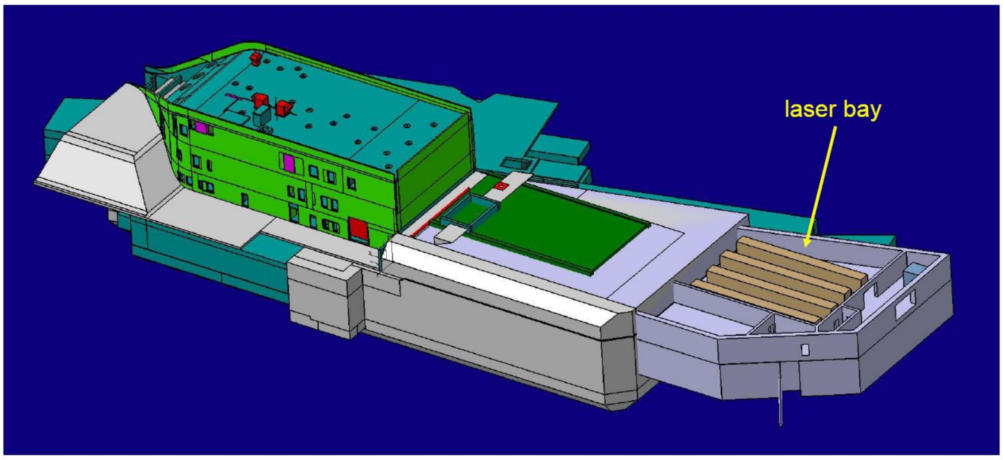
Vincent Bagnoud from GSI spoke about the fusion opportunities at GSI and FAIR (Darmstadt, Germany). He proposed a roadmap in three steps, starting with R&D, then establishing an IFE pilot reactor after 10 years, and another 10 years later building a demonstration plant. In Europe, specific simulations tools have to be developed, which should be openly accessible for publicly funded research—classified tools are not accessible for us. Finally, the laser technology and supply chains face challenges.

Vincent introduced the current state of the FAIR facility, which is under construction since 2018. At FAIR, the HED@FAIR collaboration aims for WDM creation with heavy ions. Their physics programme is mostly focused on planetary science and materials. Open scientific questions are the measurement of energy loss with ion and laser beams. The community would like to discriminate between different models for heavy-ion stopping power.

They use the PHELIX laser as a laser-based X-ray back lighter. It will be upgraded for IFE research, in particular a broadband spectrally incoherent oscillator as seed was already installed. A backscatter diagnostic will soon be commissioned, but is limited to one beam, due to the available hutch space and limited energy (200 J, 1 ns, 527 nm).

At FAIR, there is a potential to build a high repetition rate, multi beam 1–5 kJ laser with a 1 mm^2 focus and 1.3 ns, which will reach intensities of 10^{15-}–10^{16} W/cm^2. It should have a broad spectral bandwidth. Next to the APPA cave, there is 1500 m^2 space available. In 2023, intense discussion with Focused Energy took place, but it turns out that their first laser will be installed in the US. The design is funded by the European project THRILL. In collaboration with Focused Energy, a four-beam laser was laid out: Two beams will have short pulse capability but can also be used as long pulse drivers. There are two target areas in the plan, one being in the APPA cave. The timeline aims for first light in three years and full operation in five years. Combined experiments with laser and ions beams could happen from 2033.

Figure 9: *Proposed location of a laser facility at FAIR next to the APPA cave (Bagnoud)*



The specific science area that can be tackled at FAIR aims for Equation of State (EOS) measurements of warm dense matter generated by heavy ion beams. Further, they plan to perform IFE-relevant material research, energy loss measurement in plasmas, laser–plasma hydrodynamic instabilities, such as broadband laser interaction for LPI mitigation, IFE diagnostics developments, and fast ignition studies leveraging GSI’s expertise in short pulse lasers.

These capabilities will be complementary to the imaging capabilities at XFELs that address the nanoscale to micrometre scale to study fuel mix, ablator physics, and compression). At FAIR, the micrometre scale to mesoscale will be accessible to study materials, structural integrity, LPI, and energy loss. Joint IFE diagnostic developments for the European XFEL and FAIR can benefit from synergy effects, and ideally both facilities can complement each other.

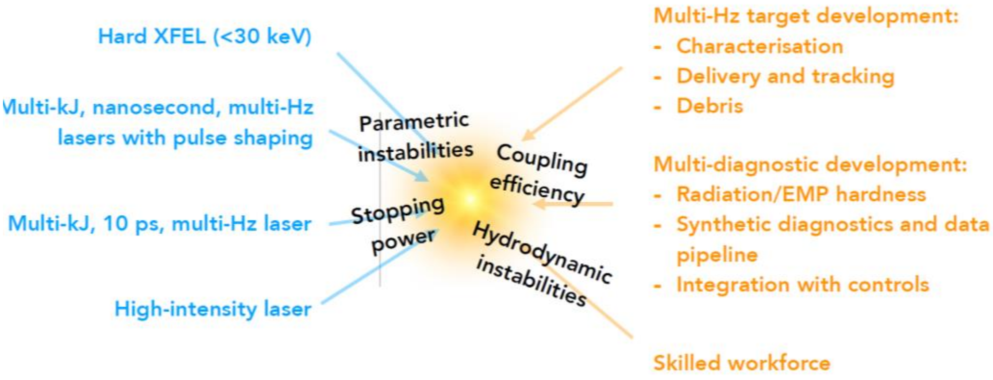
2.3.4 Future IFE research instrument

Charlotte Palmer (QUB) talked about the perspective on the contribution of a future IFE research instrument to ICF research. She introduced herself as a researcher working broadly across laser–plasma interactions and particle accelerators as well as being a member of the UK ICF consortium, the strategic advisory board of Prosperity Partnership AMPLIFI, and beyond. Charlotte underlined that diagnostics are a key driver of progress towards ignition, and recent advances in ICF gain have benefitted from increasing diagnostic capability and close interaction between measurement and modelling as well. Combining an XFEL, widely regarded as one of the most powerful diagnostic tools, with a high-power laser facility capable of generating ICF-relevant conditions would be incredibly valuable for scientific and technical advancement. She summarized current DiPOLE 100-X capabilities and emphasized that, while its maximum energy limits the processes that can be explored, its high repetition rate, matching the proposed repetition rate of future ICF-based pilot plants, already provides the opportunity for the facility to address technical challenges facing fusion energy of data management and synchronization.

Charlotte covered example studies of fast ignition, a scheme to provide an ignition spark to the pre-compressed fuel typically using a high-intensity laser to generate an energetic particle beam, often MeV protons, that can penetrate into the fuel. Key questions that need to be answered deal with the generation of a proton beam with kJ, multi-ps laser in the environment of an imploding fusion capsule, the interaction of the proton beam with dense plasma, and maximizing the coupling efficiency of the proton beam energy into compressed fuel.

Looking into the future, Charlotte spoke about technical challenges related to adapting diagnostic techniques and targets to 10 Hz operation. She stressed that an IFE power plant must run stably at a repetition rate of ~10 Hz to be a viable power source. This has implications for target delivery, diagnostics, and radiation damage. In her final slide, she, summarized a variety of needs and opportunities for an IFE research instrument as shown in Figure 10.

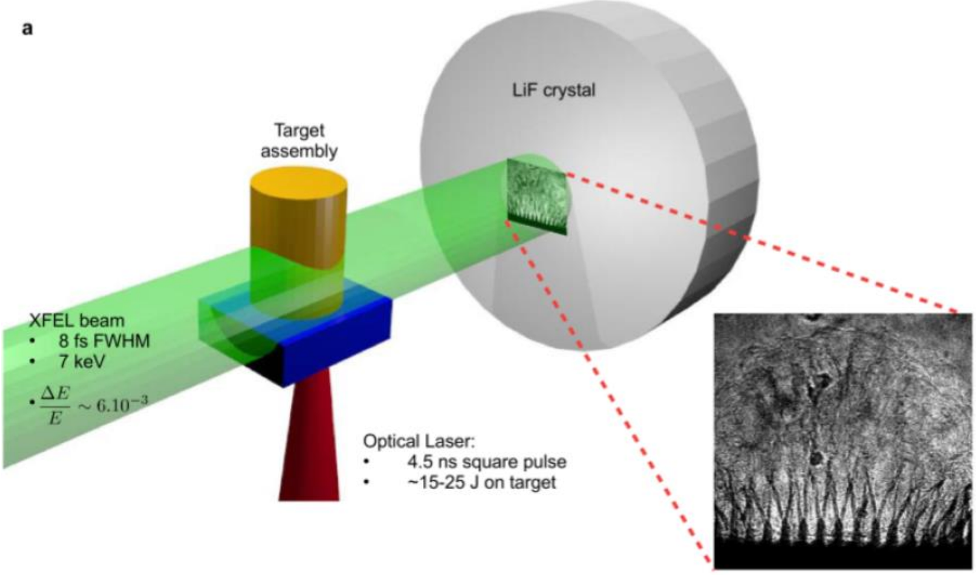
Figure 10: *IFE research instrument requirements according to Ch. Palmer*



2.3.5 Electron thermal conduction and hydro-instabilities

Pascal Loiseau (CEA) talked about electron thermal conduction and hydro-instabilities dynamics in ICF-related plasmas. He started by saying that, while the French ICF programme relies on Laser Megajoule (LMJ), it is not well-suited for microphysics studies, as it is fires only one shot per day.

Figure 11: *X-Ray radiography by an XFEL demonstrated its potentiality to image such instability [G. Rigon et al., Nature Comm. (2021)]*



Pascal stressed that microphysics matters for predicting energy scaling. There is a real need for high-repetition-rate experiments (minutes or less) to reduce uncertainties. At least two major issues may be tackled by European XFEL, coupled with a multi-kJ laser: the entire laser ablation process and its long-standing issue of electron transport, and the development of hydrodynamics instabilities and turbulence. He would welcome a >20 T magnetic field in addition to the large lasers.

The laser characteristics for an IFE are a multi-kJ at 2ω (525 nm) or 3ω (351 nm) with typically few minutes between consecutive shots. Such a laser requires a suite of diagnostics to measure laser–plasma instability losses. This is a prerequisite for precise measurements. In addition, optical smoothing (SSD and PS) and a low coherence laser are mandatory.

2.4 Round table

2.4.1 IFE research hub

Thomas Cowan (HIBEF chairperson, HZDR) outlined ideas for an IFE research hub at European XFEL. He remined the audience about the positive experience with the HIBEF user consortium during the last 12 years. HIBEF provides drivers, operations costs, personnel, and maintenance to the HED instrument. Now, with the Fusion 2040 call, public–private partnerships become necessary, and the project is mission-driven.

The participation in a future IFE research hub would work through collaboration on joint proposals, with each member pursuing individual funding, drawing from national, academic, and commercial sources.

Expressions of interest should be submitted, stating that the institution will

- Outline the group size and resources of their institute
- Plan to submit IFE beamtime proposals and become a European XFEL user
- Train students and offer education programmes
- Contribute to flagship experiments
- Participate in laser-technology discussions
- Participate in and endorse the BMBF 2040 fusion proposal for an IFE-RI

2.4.2 Emerging science cases

Dominik Kraus (University of Rostock) summarizes the presented potential science cases emerging from this workshop.

With present infrastructure, we could already pursue

- Imaging dynamic compression of wetted foams
- First shock ablator, fuel EOS, and microphysics “beyond VISAR”
- Opacities (however, not at super-extreme conditions)
- Stopping power (combine long- and short-pulse laser)
- Dynamic damage cascades (reactor wall synergy with MFE)
- High-repetition-rate operation (sample delivery and diagnostics).
- Proton acceleration for fast ignition

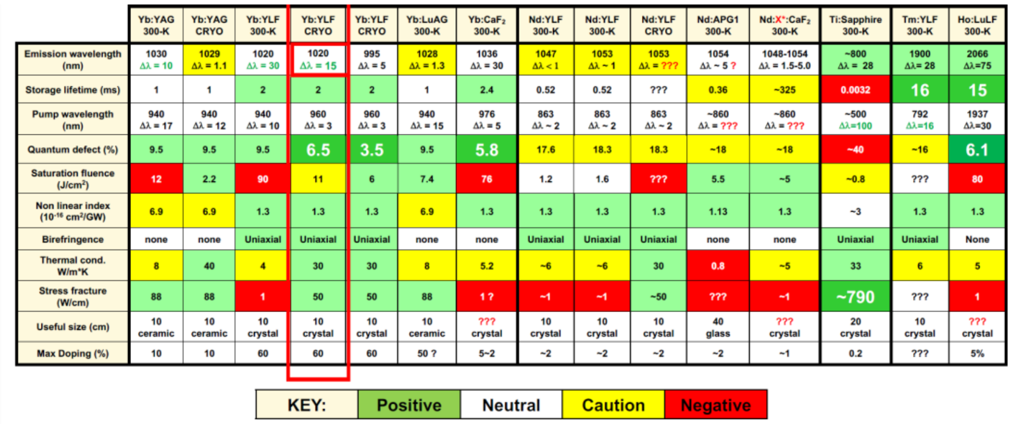
If a kJ long pulse and kJ PW short-pulse laser become available, we can extend the accessible pressure to beyond 10 Mbar and study hydrodynamic instabilities and the strength of materials. Also, proton acceleration with strong picosecond lasers can then be studied.

2.4.3 Laser technology roundtable

The following part of the workshop was dedicated to a review of laser technology.

Franz Kärntner (DESY) introduced the audience to cryogenic (liquid nitrogen – cooled) Yb:YLF and Yb:YAG lasers. His group has fundamental experience with 1J, 1 kW, 1 kHz class lasers. He proposed Yb:YLF-based lasers at the 100 J level 10 Hz, which promise very good beam quality. They can be broadband. He proposed to multiplex several of these lasers to reach multi-kJ. The broad bandwidth can be exploited to compress the pulse to 400 fs or even shorter.

***Figure 12:** Solid state laser materials for high average power / high peak power applications (Kärtner)*



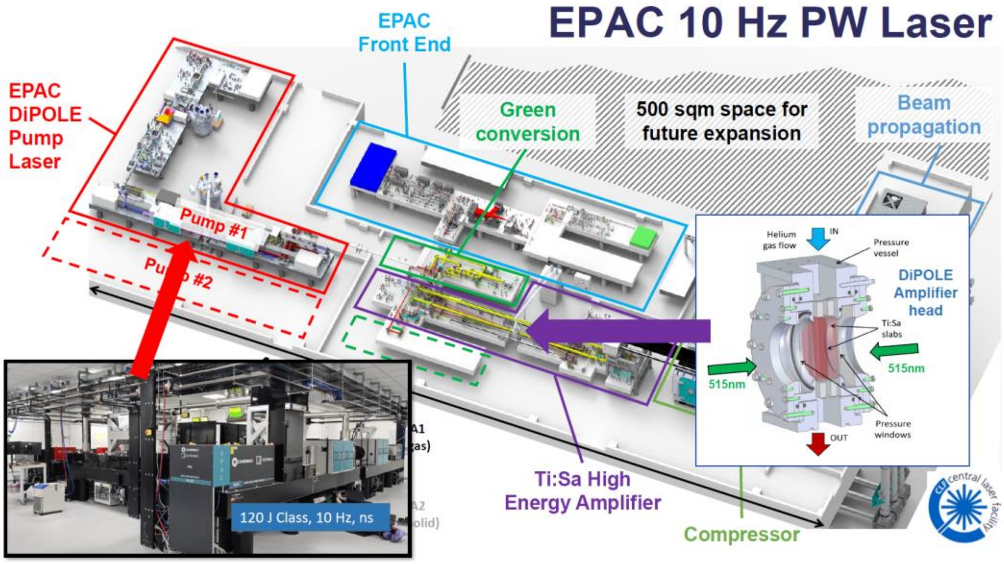
	Yb:YAG 300-K	Yb:YAG CRYO	Yb:YLF 300-K	Yb:YLF CRYO	Yb:YLF CRYO	Yb:LuAG 300-K	Yb:CaF$_2$ 300-K	Nd:YLF 300-K	Nd:YLF 300-K	Nd:YLF CRYO	Nd:APG1 300-K	Nd:X*:CaF$_2$ 300-K	Ti:Sapphire 300-K	Tm:YLF 300-K	Ho:LuLF 300-K
Emission wavelength (nm)	1030 $\Delta\lambda = 10$	1029 $\Delta\lambda = 1.1$	1020 $\Delta\lambda = 30$	1020 $\Delta\lambda = 15$	995 $\Delta\lambda = 5$	1028 $\Delta\lambda = 1.3$	1036 $\Delta\lambda = 30$	1047 $\Delta\lambda < 1$	1053 $\Delta\lambda \sim 1$	1053 $\Delta\lambda =$???	1054 $\Delta\lambda \sim 5$?	1048-1054 $\Delta\lambda = 1.5$-5.0	~800 $\Delta\lambda = 28$	1900 $\Delta\lambda = 28$	2066 $\Delta\lambda = 75$
Storage lifetime (ms)	1	1	2	2	2	1	2.4	0.52	0.52	???	0.36	~325	0.0032	16	15
Pump wavelength (nm)	940 $\Delta\lambda = 17$	940 $\Delta\lambda = 12$	940 $\Delta\lambda = 10$	960 $\Delta\lambda = 3$	960 $\Delta\lambda = 3$	940 $\Delta\lambda = 15$	976 $\Delta\lambda = 5$	863 $\Delta\lambda \sim 2$	863 $\Delta\lambda \sim 2$	863 $\Delta\lambda \sim 2$	~860 $\Delta\lambda =$???	~860 $\Delta\lambda =$???	~500 $\Delta\lambda = 100$	792 $\Delta\lambda = 16$	1937 $\Delta\lambda = 30$
Quantum defect (%)	9.5	9.5	9.5	6.5	3.5	9.5	5.8	17.6	18.3	18.3	~18	~18	~40	~16	6.1
Saturation fluence (J/cm^2)	12	2.2	90	11	6	7.4	76	1.2	1.6	???	5.5	~5	~0.8	???	80
Non linear index (10^{-16} cm^2/GW)	6.9	6.9	1.3	1.3	1.3	6.9	1.3	1.3	1.3	1.3	1.13	1.3	~3	1.3	1.3
Birefringence	none	none	Uniaxial	Uniaxial	Uniaxial	none	none	Uniaxial	Uniaxial	Uniaxial	none	none	Uniaxial	Uniaxial	None
Thermal cond. W/m*K	8	40	4	30	30	8	5.2	~6	~6	30	0.8	~5	33	6	5
Stress fracture (W/cm)	88	88	1	50	50	88	1 ?	~1	~1	~50	???	~1	~790	???	1
Useful size (cm)	10 ceramic	10 ceramic	10 crystal	10 crystal	10 crystal	10 ceramic	??? crystal	10 crystal	10 crystal	10 crystal	40 glass	??? crystal	20 crystal	10 crystal	??? crystal
Max Doping (%)	10	10	60	60	60	50 ?	5~2	~2	~2	~2	~2	~1	0.2	???	5%

KEY:	Positive	Neutral	Caution	Negative

Erhard Gaul presented on behalf of Marvel Fusion (Munich, Germany). He is looking for efficient, high peak power short pulse lasers, with high temporal contrast being a requirement. He presented strong arguments for diode pumping of a solid-state medium as well as dominantly less heating and space constraints. The current power limit of ca. 200 J per CPA laser is imposed by the available single-tile grating size for re-compression. Marvel has a 15 million dollar (M$) project to build a first laser, together with Colorado State University.

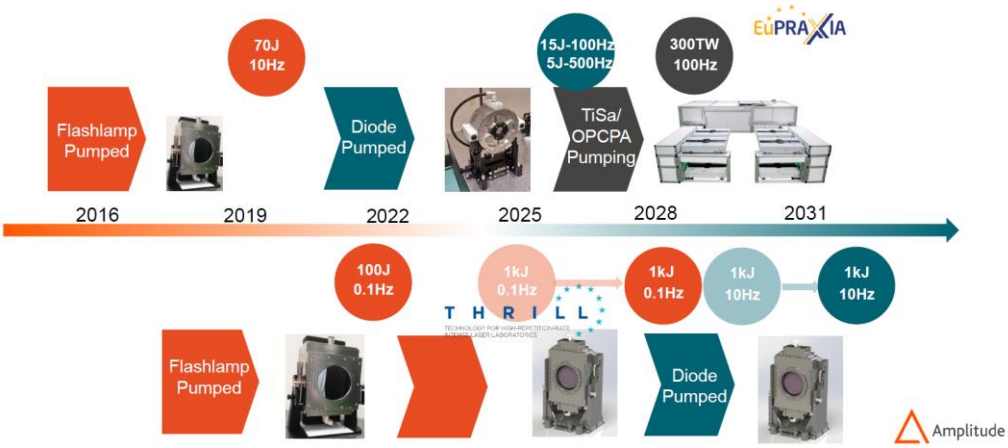
Tom Butcher (CLF, STFC, UK) mentioned that their DiPOLE platform has scalable high-energy high-repetition-rate architecture. They started with 10 J and have already scaled that to 150 J. Their own new EPAC system is a non-cryogenic gas-cooled Ti:Sa-based PW 10 Hz system. The next development is the UPLIFT project, which is funded by the UK government and is developing a 10 Hz, kJ class ns laser-driver scheme. This is the first government-level funding for laser IFE in the UK; however, there is not a dedicated laser IFE call from the UK government yet. The UPLIFT laser-works stream aims for a wall-plug efficiency of >10%, with 1% bandwidth, 1 MJ energy in less than 25 ns, and ≥10 Hz repetition rate.

Figure 13: *EPAC 10 Hz PW laser (Butcher)*



Antoine Courjaud from Amplitude (France) concluded that there is no consensus on the best approach to IFE, and therefore an IFE research laser needs to be versatile. Amplitude has already provided the RELAX laser to the European XFEL as well as a mJ pre-amplifier of the DiPOLE 100X laser. Recent short-pulse achievements with Ti:Sa lasers reach 2 PW at 10 Hz at ELI-ALPS at 50 J pulse energy. Amplitude also has references in Nd:glass shock compression lasers, e.g. for the ESRF 100 J, 0.1 Hz dynamic compression laser with pulse-shaping technology. Higher repetition rates can be achieved by switching from flashlamps to diodes. Proposals to upgrade RELAX should be discussed.

Figure 14: *Amplitudes roadmap to increased repetition rate*



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Discussions. In a general discussion following these four presentations, the following points were discussed:

- **Diode pumping**.
  Upgrading a laser from flashlamp designs to diode-pumped designs would require only a different pump geometry, but materials and heat extraction are the same. Flashlamps are much cheaper and can be used for the exploration phase. Operation costs for diodes at high repetition rate is lower, as flash lamps need to be replaced after 100 k – 10 M shots. NIF requires 1% energy output stability, but the energy in the “foot” of the compression drive is critical and must be stable within 0.1% after frequency tripling and over the entire aperture. Diodes are naturally more stable, and multiplexing pumps can be beneficial.
- **Bandwidth**.
  The required spectral bandwidth for suppressing LPIs is currently unknown.
- **Beam diameter**.
  A design of e.g. “10 kJ in 10 beams” requires to adjust the beam diameter accordingly, which depends on the materials and the saturation fluence. A 10 x 10 cm² diameter is realistic; too small does not allow a damage safety factor, but too big will reduce laser efficiency. Laser efficiency is critical because the fusion gain is limited to about 200

Broad agreement exists that the scale of multi kJ lasers need some learning about best parameters.

CLF would go away from cryogenic cooling. CLF needs to protect the proprietary part of the amplifier design, but, beyond that, they are open to collaborate. Amplitude also needs to protect proprietary parts, but new developments are shared. For Marvel, the main aim is fusion, and the laser building must be efficient and controllable.

2.4.4 General discussion

It was observed that the European XFEL IFE research ideas seem to be structured very similar to HiPER+; however, the pillar “damage of materials” is missing and should be included.

The magnetic fusion energy (MFE) community seems well organized and sells the picture that they are close to a power plant concept efficiently—maybe with less impressive results than the inertial fusion community has achieved. The MFE community claims to be a factor five away from break even and to have large investments in China, and ITER is coming up.

The audience agreed that the narrative that we just have to do the engineering and then build the power plant is far from true, and we definitely need more research. Enthusiasm for an untested concept—such as fast ignition or shock ignition, or nanowires—is dangerous and needs to be properly communicated. The participants generally would welcome expert reviews for publicly-funded programmes.

For a successful BMBF 2040 proposal, we should present and lay out in detail the research and engineering path to the power plant, but not the plant itself. We should outline where we are now and where we will go.

European XFEL is a non-profit company, and it is essential for it to keep this status. However, proprietary access is necessary for a private–public partnership. Nicole Elleuche, Administrative Director of European XFEL, said that proprietary access will not be trivial to establish as an access mode, as currently DESY and European XFEL are entirely based on non-proprietary publishable research. European XFEL has no commercial licenses, and the shareholder countries will finally decide about the use of the facility. A framework has to be worked out and should be positively evaluated by the European XFEL Council. Current data protection guidelines allow data protection for three years before they need to be made public, which could be a starting point. The strong position of the UK and France in IFE research coincides with them being also shareholders of European XFEL. It was suggested to the communities in these countries to brief their representatives and give them detailed information about the benefits of a European XFEL fusion hub.

3 Executive summary

In order to **tackle some Inertial Fusion Energy challenges at the European XFEL**, it was generally acknowledged that further research is needed if inertial fusion energy is to become a success. This research will address ablator microphysics, simpler or alternative targets (wetted foams, wire arrays), all currently unproven fusion schemes (fast electron and ion ignition, shock ignition, proton–boron fusion), the increase in gain required for a power plant, instability mitigation by wider laser bandwidth, and finally high-repetition-rate experiments.

XFELs can excel when it comes to X-ray diffraction, X-ray phase contrast imaging, small-angle X-ray scattering, and resonant probing of ionization states.

Imaging was highlighted as a unique capability at XFELs by most speakers. Here, unmatched spatial and temporal resolutions promise to offer a new level of accuracy in IFE research. The requirements were a stated as a 1 mm field of view, a spatial resolution better than 1 µm to study capsule instabilities and perturbations as well as foam dynamics, or better 100 nm with wire targets for Marvel Fusion. Indirect imaging via SAXS could resolve structures down to few 10s of nm resolution.

A time resolution sub-ps duration is required. Current laser-driven X-ray back lighters are of order 20 ps long. For the short pulse applications, like fast ignition or Marvels wire targets, 50 fs time resolution is required. The current XFEL pulse length is of the order of 25 fs and fulfils this condition.

Besides resonant probing, which requires tuning to a specific ions transition, the photon energy should generally be larger than 5 keV photon energy. In order to penetrate dense compressed material and overcome the plasma background, >20 keV are required. The European XFEL currently delivers 5–25 keV at the hard X-ray instruments.

4 Future laser upgrades at the European XFEL

A small fraction of the proposed research can already be done now at the European XFEL with the existing X-ray and laser capabilities (RELAX, DiPOLE-100X):

- High-repetition-rate operation (sample delivery and diagnostics)
- First shock ablator and fuel EOS and microphysics “beyond VISAR”
- Ablator: Micro, nano and inner-surface defects and mixing of higher-Z material into the core
  - Wetted foams as proposed mass-produced targets (EOS studies on (wetted) foams and other porous media; instabilities/homogenization in shock-compressed foams; imaging and resonant probing of ionization dynamics)
- Solid targets (nano-wire array, Marvel Fusion) with fuel
  - XFEL can probe density evolution and ionization dynamics
  - Understand dynamics inside of wires with resonant probing of the ionization states
- Opacities (however, not at super-extreme conditions)
- Dynamic damage cascades (reactor wall-synergy with MFE)

In a next step, with a moderate upgrade, in a preliminary phase, XFELs can gain the predicted insight at and beyond the 10 Mbar pressure level. Target parameters would be pressures of 10s of Mbar, temperatures up to 30 eV, and densities of equal or in excess of 10 g/cc. Such a laser is a ~5 kJ long pulse machine with a short pulse capability in 2w/3w with considerable bandwidth.

This laser in combination with European XFEL can address

- Ablators (**CH phase separation**: XFEL-based results of Frost, Kraus et al.: image all **reverberating shocks** with X-ray probe instead of just **VISAR**. This is used to time and tune the shocks to **tune a convergent ablator**: LCLS results from shocked Kapton show non-understood structures behind shock front.)
- Diamond (**Hugoniot** of nano-crystalline diamond is **offset** with respect to single-crystal diamond. This points towards voids in the diamond ablator. Study diamond **along the melt line**.)
- Evolution of hydrodynamic instabilities and ablator-fuel mixing.
- **Electron and proton acceleration (for FI)** with picosecond lasers.

Finally, a large, “sub-scale” facility for inertial fusion energy research would be an implosion facility at an XFEL, which should be able to reach ablation pressures of up to **100 Mbar.** Good candidates for targets from here could then be tested at the NIF.

The laser for this “sub-scale” facility would be a multi-beam facility with 10–100 kJ pulse energy. It is currently unclear which bandwidth is required to mitigate LPIs, as well as frequency doubling or rather tripling is necessary, and whether short pulse capabilities are needed.

- Studies of capsule stability, hydrodynamic instabilities
  - Answer open questions in microphysics models
  - **Capsule shape** unknown below 1 µm resolution. Observed **perturbations**, but unable to see **seeds** form during flight. >20 keV needed (background), and sub-ps temporal duration. (Current back lighters are 20 ps.)
  - Factor 3x change in **thermal conductivity** causes 4x larger peak–valley density modulations. Resolution needed to see this is currently not available; X-ray might be the solution.
  - Hot spot **stopping power** and **X-ray opacity**, ionization states. XFEL can diagnose these.
  - How does the burn wave **burn into the fuel**?

It is our current understanding that the details of a laser system and which physics to study depend on results of the preliminary phase.

Figure 15: *Aerial view of the current European XFEL research campus in Schenefeld near Hamburg*

A References

[1] Zastrau et al.: “The High Energy Density Scientific Instrument at the European XFEL”, J. Synchrotron Rad. **28**, 1393–1416 (2021) doi:10.1107/S1600577521007335

Acknowledgements

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