FACILITY FOR ANTIPROTON AND ION RESEARCH

Laser-based pump-probe equipment for the APPA cave at FAIR

Technical Design Report for the HEDgeHOB/WDM collaborations at FAIR

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In a typical laser experiment the interaction with matter creates a plasma (left) and the energy penetrates the target in form of shock waves or particle kinetic energy. The high-energy cave at FAIR will allow diagnosing what happens inside the target during the interaction.
# Table of Contents

1. Objective and executive summary ................................................................. 3  
2. Science case ................................................................................................. 5  
   2.1. A quick look deep inside extreme, dense matter .................................... 5  
      2.1.1. Direct laser shock wave loading of solids ....................................... 5  
   2.2. High-energy laser driven backlighting of heavy-ion heated extreme matter states - first plasma physics experiments at FAIR .................................................. 8  
3. Experimental equipment .............................................................................. 14  
   3.1. Parameters .............................................................................................. 14  
   3.2. System Overview and energy budget ...................................................... 15  
   3.3. Target area and dedicated diagnostics .................................................... 17  
   3.4. Beam transport ...................................................................................... 17  
   3.5. Frequency doubling and high-energy amplifier ....................................... 19  
   3.6. Low energy part of the system ............................................................... 24  
   3.7. Control system ....................................................................................... 27  
   3.8. Timing system ........................................................................................ 27  
   3.9. Wavefront budget and wavefront control ............................................... 29  
4. References ..................................................................................................... 31  

## 1. Objective and executive summary

The objective is the addition of a diagnostic development and pump-probe capability in the APPA cave. This equipment is based on a mid-scale laser dimensioned to fit within the existing space and budget and which fulfills the requirements for the experiments planned during the start-up phase of FAIR.

One main goal at FAIR is the active backlighting with highly penetrating x-ray radiation of matter heated to the state of warm dense matter (WDM). Backlighting is one of the primary diagnostic tools to access plasma parameters and structural information from inside the dense samples. Intense x-ray pulses with sufficient brightness to probe the short-lived samples can be obtained from high-energy laser-driven plasmas. In addition, advanced Backlighting schemes based on laser-accelerated electrons and neutrons have also recently been proposed. Probing the millimeter-size high-Z targets foreseen in the plasma physics program when FAIR reaches its full anticipated ion beam intensity will require highly penetrating hard (>100 keV) x-ray sources and energetic particles, typically obtained from large scale PW-class CPA laser systems delivering focused intensities in excess of $10^{18}$ W/cm². However, already in the initial version of the accelerator, the first uranium beams expected in the FAIR commissioning phase will achieve unprecedented intensities allowing rapid heating of matter beyond the melting point thus accessing the strongly coupled plasma regime. For diagnosing such samples backlighting with softer x-ray radiation (VUV to keV) will reveal important structural information that can be directly compared to...
results from state-of-the-art dense matter modelling. Laser-plasma sources in this energy range can be generated with 100 J-class long-pulse (nanosecond) lasers, reaching focused intensities in the range of $10^{12} \ldots 10^{16} \text{ W/cm}^2$. A second feature available in the early days of the APPA cave will be an accelerator-driven proton microscope with very high spatial resolution. The proton microscope together with time-gated detectors allows for studying rapid transient phenomena by doing density measurements at a precision level never obtained before. The equipment proposed in this TDR allows driving pump-probe experiments, in which the laser is used as a WDM driver and the accelerator as a probe.

For this reason, the current document describes the installation of a preliminary laser setup at the APPA cave that will enable commissioning experiments during the start-up phase of the accelerator. In addition the laser will be used for off-line diagnostic developments.

A secondary goal of the project is the development and test of laser components which will be ultimately needed for the realization of the full FAIR program. Here, operation of high-energy lasers (>1 kJ) at a repetition rate matched to the shot rate of the FAIR machine (1 shot per 5 to 10 min in the APPA cave) has been identified as a major issue. Although some preliminary work exist in the USA, this technology has not been demonstrated at the level necessary for FAIR and therefore a test-bed is highly desired to reduce risks. The technology developed and tested during the project fulfills this goal. It will be also of high interest to other Helmholtz projects like the HIBEF project at the European XFEL or the European project ELI.

The project proposed here is of moderate size and fulfills the requirements for many day-one experiments in the APPA cave at FAIR. Outside of the laser beam-line, the rest of the investment could be re-used after the experiments are completed, either locally for off-line diagnostics development and/or the upcoming Helmholtz Beamline at FAIR.
2. Science case

The described equipment will allow experiments in the first days of FAIR in the APPA cave. The experimental capabilities enable pump-probe types of arrangements. In the first series of experiments, the laser will be used as a driver to launch multiple shocks in various samples, and a proton beam together with a time-gated detector will be implemented. Intense heavy ion beams from the FAIR facility offer a unique tool to generate matter at high energy density for accurate experimental studies of these extreme matter states.

In a second series of experiments, we propose two example cases demonstrating the potential of the proposed equipment for diagnosing plasmas generated in the early commissioning phase of FAIR, thus enabling novel and exciting science when FAIR becomes operational.

2.1. A quick look deep inside extreme, dense matter

The response of matter at high energy density can be explored starting at day one of the FAIR project. The FAIR facility will be able to deliver unprecedented intensities of energetic protons, which can be used to look deep inside any material with high spatial and temporal resolution. The concept of proton microscopy has been successfully tested using the LANL LANSCE [1] facility and the GSI PRIOR project [2]. States of high energy density can be generated using direct or indirect shock loading using the proposed laser system [3]. For the day one experiments two baseline experimental setups can be realized as described in the following

2.1.1. Direct laser shock wave loading of solids

The proposed laser system can deliver 100 J in short, tailored pulses. Such pulses, when individually timed will launch shock waves into a test sample, where each shock-strength can be chosen using the respective laser pulse intensity. As the first shock wave propagates through the sample it alters the condition for the propagation of the following one. Standard techniques at other laboratories need to observe the shock break-out at the end of the sample and derive the internal material parameters assuming a constant shock velocity inside the material [4]. At FAIR, using the proton microscopy not only the propagation and possible coalescence of multiple shock waves can be explored already in the first campaign, but also any deviation from a linear behavior, the shock wave curvature, interaction with internal structures and many more features can be explored directly. Internal material interfaces or inclusions can be exposed to multiple shock waves and monitored in real time (see an example at lower resolution in Figure 1).

The temporal resolution is as critical as the spatial resolution for such transient experiments. The spatial resolution is governed by the proton kinetic energy, which is unmatched at FAIR compared to all other facilities using proton microscopy, while the temporal resolution can be enhanced from the intrinsic bunch length (100 to 50 ns) using gated, fast detector systems. At a typical shock wave velocity of 2.5 km/s a shock wave moves 10 µm in 4 ns. So to avoid
spatial blurring the temporal resolution has to match or even exceed that value. Here the only limit is the
signal to noise ratio, directly related to the intensity of the proton bunch. Using the high proton numbers
in the bunch delivered by the FAIR facility $10^9$ protons in 2 ns will be available for imaging already in the
initial state using fast shutter camera systems (see Figure 2).

Thus FAIR offers the highest spatial and temporal resolution for these experiments. As a possible
extension of these experiments even a pre-compressed state of matter can be envisioned using either
Diamond Anvil Cells (DAC) or pre-compression using a part of the laser beam. These first-day
experiments also will pave the way to the full capability of the FAIR APPA cave once the final laser
system will be installed giving access to higher and more versatile experimental conditions.

2.1.2. Two-step laser-driven shocks

The second experimental layout as a first-day experiment is the use of the proposed laser system not
directly on the sample of interest, but using a ramp compression scheme and launching a solid impactor
to hypervelocity conditions [5].

This second scenario offers two main complementary possibilities: As the laser is evaporating a thin
polymer foil the x-ray background is very limited. The
expanding foil ramp compresses and accelerates a flyer plate
to velocities of several km/s (Figure 3), while keeping its
temperature well below the melting point. Thus, a solid
impactor with extremely well known initial conditions
interacts with the sample material of interest. The
experimental prerequisites to produce and tailor these
complex targets have been developed at TUD within the
recent years [6]. While this method only allows for a single
shock the difference to the direct drive is no pre-heating due
to electrons or x-rays of the sample. Initial experiments and
simulation have shown that we can reach conditions highly
relevant for e.g. space applications (space debris, impact of interplanetary objects) and at the same time
have unprecedented diagnostic capabilities using the FAIR proton beam.
Using the FAIR accelerator in a different operating regime up to four bunches can be delivered within a microsecond. The first three can be used to image the condition and position of the flyer plate while the fourth can be imaged with higher temporal resolution on the detector to monitor the shock wave propagation or density change inside the sample. An example at much lower resolution is shown in Figure 4 for impact velocities of about 1.4 km/s. At higher resolution smaller impactors can be driven to velocities of 15 km/s (see Figure 5).

### 2.1.3. Experimental setup

The experimental setup for both approaches is very similar and relies on the illumination of targets with the driving laser and their diagnosing using the FAIR proton microscope PRIOR as depicted in Figure 6. In both cases, the interaction generates shocks that propagate through the target at 90 degrees from the ion beam-line. The shocks will be characterized using standard techniques such as VISAR, which monitors the shock velocity as it exits the target at its rear face. Preliminary work is being currently done at GSI to develop a VISAR suitable for such applications. If necessary, preparatory beam-times will be requested at the PHELIX facility to characterize and test the targets.
A preliminary version of the proton microscope is under development at GSI in order to gain experience with such a device and explore its capabilities. At the time when FAIR comes online, the equipment will be moved to the APPA cave and will be fully commissioned. The success of this experiment relies also in part on the availability of time-gated detectors for imaging small time windows and avoiding blurring effects that would reduce the image resolution. The camera system will be developed in the next years for that application.

All in all, the necessary equipment and know-how for this experiment is going to be developed in advance off-line and will be moved to the APPA cave as soon as technically possible so that this experiment can yield data very soon after the commissioning of the FAIR facility and the APPA cave.

### 2.2. High-energy laser driven backlighting of heavy-ion heated extreme matter states - first plasma physics experiments at FAIR

Intense heavy ion beams from the FAIR facility offer a unique tool to generate matter at high energy density for accurate experimental studies of these extreme matter states. Active backlighting with highly penetrating x-ray radiation will be one of the primary diagnostic tools to access plasma parameters and structural information from inside the dense samples. Intense x-ray pulses with sufficient brightness to probe the short-lived samples can be obtained from high-energy laser-driven plasmas. Probing the millimeter-size high-Z targets foreseen in the plasma physics program when FAIR reaches its full anticipated ion beam intensity will require highly penetrating hard (>100 keV) x-ray sources, typically obtained from large-scale PW-class CPA laser systems delivering focused intensities in excess of $10^{18}$ W/cm².

However, the parameters of the accelerator available during day-one experiment times will not reach the full capability of the accelerator yet. Nevertheless the first uranium beams expected in the FAIR commissioning phase will achieve unprecedented intensities allowing rapid heating of matter beyond the melting point thus accessing the strongly coupled plasma regime. In the case of low Z materials like aluminium, the initial FAIR parameters turn out to be nearly ideal for such studies. For diagnosing such samples backlighting with softer x-rays (VUV to keV) will reveal important structural information that can be directly compared to results from state-of-the-art dense matter modelling.

Laser-plasma sources in this energy range can be generated with 100J-class long-pulse (nanosecond) lasers, reaching focused intensities in the range of $10^{12} \ldots 10^{16}$ W/cm². So in the following we propose two example cases demonstrating the potential of such a laser system for diagnosing plasmas generated in the early commissioning phase of FAIR, thus enabling novel and exciting science when FAIR becomes operational.
2.2.1. Testing electronic structure modelling in WDM by opacity measurements

Radiation transport often plays an essential role in both astrophysical and laboratory high-energy density (HED) plasmas and a key material property is the opacity, which quantifies the coupling of the radiation into matter and determines how transparent or opaque the plasma is to radiation. At high densities, the optical properties of strongly-coupled plasmas are very sensitive to the electron energy spectrum defined by inter-particle interactions. Theoretical modelling of opacity is particularly challenging in the Warm-Dense-Matter regime characterized by strong ion coupling and partial degeneracy where traditional expansion schemes for small parameters fail and multi-body particle correlations and quantum effects have to be taken into account. A well-known approach based on the Liberman model is the average atom approximation [7]. The opacity group at the Keldysh Institute of Applied Mathematics (KIAM) has a suite of opacity codes based on this approximation [8]. In particular at higher densities the choice of boundary conditions can have a strong effect on the results. Another approach which also takes into account the ion-ion correlations are Quantum Molecular Dynamics simulations (QMD). Mazevet et al. have compared QMD calculations of the optical properties of aluminium at solid density and temperatures up to 2 eV. Especially at densities approaching solid density, they find large differences with standard opacity codes based on isolated atom cross sections [9].

Due to the complexity of opacity models and the approximations, experimental validation is crucial. The great challenge for meaningful benchmarking opacity measurements lies in the generation of a sample at high energy density at well characterized and homogenous conditions. Here, intense heavy ion beams offer an intriguing path towards large homogenously heated samples. The WDM-collaboration is one of the two large collaborations with approved proposals to conduct research on dense plasmas at the upcoming FAIR facility. A strong focus of the WDM-collaboration is on the emission, absorption, and scattering of electromagnetic radiation from warm-dense matter.

As was shown in [10], heavy ion pulses as expected in the commissioning phase of FAIR ($10^{10}$ U-ions in 100 ns) will deposit an energy of the order of 10 kl/g in high-Z targets. Employing thin foil targets results in a strongly coupled plasma at temperatures exceeding 1 eV with an almost constant temperature distribution (see Figure 7 Figure 8- left) with sufficient transmission to allow opacity measurements in...
the VUV spectral region. Figure 7 (right) shows a comparison of the transmission in this spectral region, calculated for the anticipated plasma conditions using two different opacity models. Large discrepancies are found, which stem from different approximations used to incorporate high density effects. This shows that such a measurement would provide important benchmarking data for opacity modelling in the warm-dense matter region, where besides our colleagues at the KIAM, many other theoretical groups (U. Oxford, U. Rostock, LULI, CEA, LANL) are working on opacity models and techniques to extract optical properties of warm-dense matter from numerical simulations.

2.2.2. X-ray diffraction on high-temperature carbon

Carbon is an extremely interesting material both from the fundamental standpoint as well as for its many technological applications. The high pressure phase diagram of carbon is far from being understood, with large discrepancies in the predicted melting line and phase boundaries. Both the metastable diamond phase and the predicted bc8 phase are likely to play an important role in understanding the interior structure and dynamo process inside carbon-rich planets. Technologically, carbon is important due to its outstanding material properties, such as high melting point, electron mobility and thermal conductivity. These make it a promising material withstanding extreme environments. Graphite is being considered an important first wall material candidate in magnetic confinement fusion reactors. In ICF research, high-density carbon is a promising ablator material. Last but not least, at ion beam accelerator facilities, such as FAIR and the LHC, carbon is used in beam dumps for relativistic intense heavy-ion pulses, and first calculations and experiments show a significant range increase due to hydrodynamic tunneling.

Pump-probe experiments have gained important insight into the exotic material properties of carbon at extreme conditions. Results obtained by scattering laser-driven x-rays on samples, probing the amount of molten material heated by laser-generated proton pulses, shows that the high-temperature liquid phase is still largely unknown. More recently we have performed time-resolved x-ray diffraction measurements at the Titan (LLNL) and PHELIX (GSI) laser facilities. The results indicate that the ultra-fast heating by laser-generated protons or supra-thermal electrons resulted in highly non-equilibrium systems.

The FAIR facility will offer an intriguing complementary approach to the volumetric heating of solid targets. Stopping ranges of relativistic (GeV/u) heavy ions are in the range of centimeters, thus providing homogenous energy deposition over mm-sized targets while the temporal scale of order 100ns results in samples at LTE conditions. This approach thus enables accurate studies of carbon at extreme conditions, which cannot be produced in such clean and well-characterized conditions by any other technique. As a possible first experiment at FAIR, we propose x-ray diffraction studies in graphite, quasi-isochorically heated by the FAIR heavy-ion beams in the early commissioning phase. Novel insight into carbon at these extreme conditions will be enabled by a 100 J-class laser system to drive the x-ray probe.

2.2.3. Preparatory work

In a generic opacity measurement the transmission of a probe (“backlighter”) is spectrally resolved and by comparison with the un-attenuated source the absorption is determined. The components of central importance to an opacity measurement are thus a broadband radiation source and a spectrometer, both in the spectral range of interest. We have started to design these components and have performed proof-of-principle experiments to show the viability of our approach.
An efficient spectrometer based on a large-aperture blazed flat-field grating has been built. The spectrometer works in the VUV spectral range at wavelengths between 40 and 120 nm and employs a back-thinned CCD detector achieving both high resolution and quantum efficiency.

As the detection scheme is time-integrated the duration of the probe needs to be sufficiently short compared to the temporal evolution of the heavy-ion heated plasma, which is on a time scale of some tens of nanoseconds. High brilliance is required to generate a sufficiently strong signal necessary for accurate determination of the transmission, and to overcome other experimental noise sources. In addition the backlighter source should ideally be a broadband source to allow a wide spectral range to be covered simultaneously. These requirements are well-fulfilled by laser-produced high-Z plasmas. At laser intensities of order $10^{12}$ W/cm$^2$ in nanosecond long pulses a highly collisional thermal plasma is generated with thousands of closely spaced transitions resulting in a quasi-continuous emission spectrum. Both source size and emission duration are closely linked to the laser focal spot size and pulse duration, allowing to generate an intense pulsed VUV source with ns duration and sizes down to 100 μm. First tests using a Joule-class Q-switched Nd:YAG laser to drive the backlighter source were able to demonstrate single-shot opacity measurements from cold samples. In a proof-of-principle experiment at the HHT experimental area at GSI, we were able to measure the opacity in heavy-ion heated Bi-foils. Due to the limited ion beam intensity available at HHT, only heating to just above melt temperature could be achieved. Also, the low-power backlighter source limited the experimental error on the transmission measurement to ~ 20%. This shows the potential of our approach for future opacity studies at FAIR. However, a significant increase in photon numbers is necessary to generate high-quality single-shot data and to allow spatial resolution.

### 2.2.4. Experimental setup

The setup foreseen for opacity measurements is shown in Figure 8. Opacity experiments using the first FAIR ion beams would employ uranium ion pulses of $10^{10}$ ions/bunch focused to approx. 1 mm spot size to heat thin (<0.5 μm) high-Z foils to eV temperatures. Using the proposed laser system with up to 100J laser energy will yield a significant increase in source brightness, resulting in a high signal-to-noise ratio for accurate opacity measurements. This will permit the use of reflective optics for the VUV radiation where the Institute for Optics and Fine Mechanics IOF (Jena) has demonstrated reflectivities of up to 30%. Employing such optics for VUV beam transport and shaping will allow simultaneous probing of the
sample over an extended region across the target, encompassing both the heated region and unheated material. A novel spectrometer setup will deliver space-resolved transmission measurements.

The laser will be focused onto the backlighter target to a line focus of dimension 6 mm x 300 μm (this is accomplished rather easily by introducing a small amount of astigmatism, either by use of cylindrical optics, or by using a spherical focusing mirror in an off-axis geometry), reaching an on-target intensity of $10^{12}$ W/cm² (100 J pulse energy, 5 ns pulse duration). The line-shaped source plasma is then re-imaged by a spherical VUV mirror onto the target with a 3x demagnification (i.e. to 2 mm x 100 μm). In one dimension the probed region thus crosses both unheated material as well as the entire heated part, while in the other dimension it lies well within the heated region, thus avoiding averaging over in-homogeneities towards the beam edges. The spectrometer is a novel design, which by use of an off-axis spherically curved VUV-mirror provides spatial resolution in the non-dispersive direction. Ray-tracing calculations of this modified setup suggest that spatial resolution well below 100 μm should be achieved. The spectral resolution ($\delta\lambda/\lambda$) is usually limited by remaining aberrations of the varied line spacing grating and the detector pixel size to approximately 1000. Our modified setup introduces additional aberrations resulting in a slight deterioration of the resolution to about 400. Nevertheless, given the strong differences in the opacity model predictions this resolution is well sufficient to discriminate between theories.

We have employed the modified spectrometer at an experiment at the PHELIX facility. The high-intensity PHELIX laser was focused onto a thin metal foil to isochorically heat it to several 10s of eV and the spectrometer was used to provide a 1D-image of the emitted VUV-spectrum. The observed extent of the VUV-emission corresponds well to the simultaneously measured image of the K-alpha emission, indicating high spatial resolution was obtained. The spectral resolution could not be assessed as the VUV-emission was broadband. Such test measurements will be performed at a dedicated testing setup.

The setup proposed for studying high-temperature carbon is depicted in Figure 9. Pulses of $10^{10}$ Uranium ions at energies of 1 GeV/u are expected when the FAIR facility goes into initial operation. Targets will consist of thin slabs (<50 μm) of highly-oriented graphite, coated on thin glass slabs. The targets with transverse dimensions of a few mm will be oriented parallel to the incoming ion beam. As the range of ions at 1 GeV/u in solid density carbon is several centimeters, homogenous heating along the entire sample is obtained.

Probing by x-ray diffraction will be enabled by a laser-generated x-ray line source. Focusing laser pulses with an energy of 100 J and 1 ns duration onto a 100 μm spot results in on-target intensities of $10^{15}$ W/cm². This intensity is optimum for generating a hot thermal plasma emitting line-radiation of highly
charged ions. Using a thin titanium foil as a backlighter target yields intense emission of the Ti He-alpha resonance line at 4.75 keV. For laser light at 527 nm wavelength, conversion efficiencies of laser energy into this line of $10^{-3}$ are routinely achieved (e.g. [11]), thus yielding $>10^{14}$ photons for a 100 J laser pulse.

Diffraction off the (400)-plane of the graphite crystal at a Bragg angle of $\approx 51^\circ$ will be detected by means of large imaging plate detectors, which offer quantum efficiencies approaching unity for keV photons. The Bragg condition is fulfilled along a circular arc at constant incident angle on the target surface which will cross the entire heated area as well as unheated parts of the crystal, projecting these areas with large magnification onto the detector. The expected signal can be estimated using the known reflectivity of oriented graphite of $\approx 1$ mrad. A resolution element of 50 $\mu$m on the crystal has an effective solid angle of close to $10^{-7}$, thus several $10^6$ detected photons per resolution element can be expected. This will yield a strong and low-noise diffraction signal, allowing accurate determination of the ionic disordering upon heating. Also, an increasing of the inter-plane spacing as the target expands should be observable as a displacement of the diffraction rings. As an additional option, hydrodynamic motion can by suppressed by tamping of the heated graphite with up to 100 $\mu$m CH, which can still be penetrated by the probe x-rays.
3. Experimental equipment

The equipment described below fulfills the requirements to drive pump-probe experiments during the startup phase of FAIR as described above by the science case. For these experiments, the laser can be used as a shock driver or as a soft x-ray and x-uv source. The description of the various elements of the system is made from the target area (that conditions the requirements) up to the laser sources.

It is important to note that the laser will not be able drive the full program of the HEDgeHOB collaboration in the APPA cave. For that, a multi-kilojoule petawatt high-energy laser with two beamlines is required. A first proposal for such a laser has been made in the initial version of FAIR but its technical feasibility has been hindered by the changes made to the accelerator layout introduced after the modularized approach was decided. However, within the new layout of FAIR, a space located between the APPA cave and the High-Energy Storage Ring has now been reserved for a high-energy petawatt laser.

Among the technical bottlenecks of such a project, the operation of kilojoule amplifiers at high short rate has been identified as a major issue. The proposed equipment acts also as a test-bed for such an amplification module and it therefore of high importance for the APPA collaborations (HEDgeHOB, WDM, SPARC and BioMat).

3.1. Parameters

Table 1 shows an overview of the main characteristics of the experimental equipment required for the day-one pump-probe experiments described above. The parameters describe those of a laser beam in the target area.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pulse energy</th>
<th>Pulse duration</th>
<th>Pulse shape</th>
<th>Repetition rate</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>100 J</td>
<td>100 ps</td>
<td>20 ns</td>
<td>1/10 min</td>
<td>1/1 min</td>
</tr>
<tr>
<td>tolerance</td>
<td>min</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
</tbody>
</table>

The laser is designed for operating in two modes. The first mode delivers a single pulse of 100 ps. This duration has an impact on the fluence that one can tolerate on the optics as the operation of lasers with short pulses reduce the damage threshold of the components used. The second mode of operation will deal with shaped pulses. In the scientific justification, only parabolic pulses have been considered. A 20 ns long parabolic pulse has a full with half maximum of about 5 ns (the maximum 20 ns refer to the maximum time window and not the actual pulse width). Although the longer pulse duration will be beneficial in term of laser-induced damaged, non-linear effects like the frequency doubling will be strongly impacted. The solution resides in having a set of non linear crystals (probably two at the beginning) to be able to address the two proposed schemes.
3.2. System Overview and energy budget

3.2.1. Schematic overview of the laser system

A schematic view of the laser architecture is presented in Figure 10. The general idea behind the architecture is to leverage the existing expertise at GSI and at the participating institutions in order to gain time and reduce the risks. An additional factor is the cost of operation of these elements since the spare parts are common to other lasers like PHELIX. The existing components or those where the visibility is very high are depicted in green. The proposed architecture relies on a programmable nanosecond front end similar to the one used at PHELIX. For this a commercial solution from the company Photline or equivalent could be used. The shaped nanosecond pulses are then amplified in a regenerative amplifier up to the millijoule range. The long pulses require a non-standard cavity. This could be done using the existing degenerate ring cavity used at GSI or a more robust design based on a linear highly mode-selective cavity like the one in reference [12].

The exact cavity architecture will be developed during the project initial phase. The budget required by this development step is negligible as the main components are common to all the concepts of architecture which have been discussed until now. After the regenerative amplifier, the beam is sent to the glass pre-amplifier, whose input plane determines the initial image plane for the whole power amplifier. Here the beam spatial profile will be shaped using a serrated aperture to reach a top hat profile at the output of the rod-based pre-amplifier. Based on data collected at PHELIX, only a weakly “cut” beam is necessary as the radial gain of the rod amplifier strongly amplifies the edges of the beam. As a consequence a high throughput of the serrated aperture can be achieved but a fine tuning of the input beam size is necessary. This is usually obtained with a three-lens adjustable telescope.

The main amplifier is the original and high-risk part of the project. Here some development is required to keep the repetition rate of the system and reach the targeted value. This amplifier is described in the following. The gain of this amplifier should reach a factor of 10 to deliver about 200 J at the fundamental laser frequency.

The last stage in the laser room is the frequency conversion. After this stage, the beam is imaged-relayed to the target chamber through-out vacuum tubes to avoid turbulences induced by the non-temperature controlled environment.
<table>
<thead>
<tr>
<th>Location</th>
<th>Front end output</th>
<th>Regenerative amplifier</th>
<th>Preamplifier input</th>
<th>Preamplifier output</th>
<th>Main amplifier output</th>
<th>Frequency conversion output</th>
<th>on Target chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy</td>
<td>nJ</td>
<td>20 mJ</td>
<td>10 mJ</td>
<td>20 J</td>
<td>200 J</td>
<td>120 J</td>
<td>100 J</td>
</tr>
</tbody>
</table>

**Table 2: Energy budget of the laser**

The energy budget of the whole system is depicted in the Table 2. Some margin has to be built into the system. For the low energy part of the system, our experience shows that such system can be delivered with an energy margin. Therefore the design can be considered as conservative. The energy gain factor of the main amplifier is the only parameter where we expect a small or no margin.

### 3.2.2. Implementation in the APPA building

A CAD view of the building is shown in Figure 11. The laser is located in the second floor of the APPA building, next to the main control room of the cave. The laser will be image-relayed to the target area located in the cave. The position for the hole necessary for feeding the laser beam into the target area is mostly dictated by radiation safety considerations. After amplification and frequency conversion, the beam will be transported in vacuum tubes. This avoids the effects of air temperature gradients and also ensures a higher level of safety when the interlock system of the laser is connected to a measurement of the pressure in the beam line.

![Figure 11: 3-D view of the vacuum laser beam-line in the APPA building. The vacuum beamline is depicted in red.](image)

The laser is installed in a ~100 m² laboratory that will be equipped with clean room flow boxes and already benefits from a temperature controlled environment. A view of the building floor plan is showed in Figure 12 that includes the dimension of the 14 x 7 m² laser room (as “Diagnostikraum” in grey). The laboratory is located next to the control room, which allows for a simple fast and slow timing architecture. A side room (also overlaid in grey) is also available for power conditioning units. We foresee also to use the laser there for off-line diagnostics development in the room named “Exp. Vorbereitung”. From the laser room, a vacuum beam-line image-relays the beam to the target area.
The equipment is made of blocks which are state of the art of laser technology and mostly originate from proven PHELIX subsystems like its Preamplifier. Therefore we expect that the development costs associated with the project will be limited to the high-energy amplifiers, while the rest of the system will either be based on commercial solutions or existing solutions at GSI. Because of the compatibility with PHELIX, the cost for the laser is very low and the development risk on the low energy part of the system is small. After the startup phase of FAIR, the components could stay in place for diagnostics developments, be used as source for other applications (VISAR) or as in-kind for the Helmholtz-Beamline project at FAIR. In this view, the equipment is fully compatible with foreseen equipment and technology of the Helmholtz Beamline, which will make the maintenance (spare part management and know how) much easier and cost effective.

### 3.3. Target area and dedicated diagnostics

The target area (target chamber and diagnostics) is part of a different TDR. The target chamber is a very hostile environment for laser components because of the amount of debris generated by the targets and activation. The experimental setup and laser delivery equipment placed inside the target chamber will therefore be very limited if not absent. For all experiments, we expect to have the last focusing optics (lens) located outside the chamber behind a debris shield. The diagnostics necessary for the experiments like time-gated cameras and spectrometers are described also in another TDR.

### 3.4. Beam transport

#### 3.4.1. Concept and requirements

A top view of the laser beam-line is shown in Figure 13. The total distance from the laser room to the target chamber is 72.35 m. This distance compares with the existing distance between the PHELIX switch yard and the target chamber at Z6 in the experimental hall of GSI, for which GSI has gathered expertise.
There are enough straight distances so that one can use two lens telescopes as imaging tools. For that matter, all the space for feeding the beam through walls has been reserved.

Figure 13: Top view of the laser beam-line inside the building.

### 3.4.2. Beam size

The beam size is determined by the maximum energy that one expects to transport through the beam-line to the target area. In order to avoid air fluctuations, the beam-line will be evacuated and fully imagerelayed. For a 100 J pulse with a fill factor of 60% (a typical value for PHELIX is 70%), a 12-cm diameter beam (value at 1% in intensity) gives a maximum fluence of 1.5 J/cm², which is sufficient to avoid damage with 100 ps long pulses. With AR coatings specified at 10 J/cm² and HR at 15 J/cm² in 1 ns which are commercially available, one has an operation point located between 2 and 3 times below the damage threshold of the specified optical components. This should ensure a safe operation and low maintenance of the laser over time.

### 3.4.3. Losses and wavefront budget

After frequency conversion and during beam transport, wavefront quality requirements are relatively modest for this project. One wave of wavefront error (Peak-to-Valley) can be tolerated for the whole beam-line. Using a weak requirement of λ/4 wavefront distortion per optical element (6 mirrors + 4 lenses) should ensure a cost effective solution.

The transport losses, on the other hand, are to be reduced, in such a way that the energy transmission of the beam-line exceeds 80%.

### 3.4.4. Vacuum equipment

The vacuum equipment is based on turning boxes used in the 100 TW beam line at PHELIX [13,14]. The current boxes accommodate 200 mm mirrors and their mounts, which would allow working with the expected beams. The turning boxes have been designed outside but GSI owns the drawings of the equipment at stake. The existing beam line is however difficult to maintain and align. To ease alignment, the added cost of increasing the mirror size to 250 mm is being looked at. In such a case, a redesign of the turning boxes and support is also necessary. Once the initial alignment has been done, the beamline
should be easy to maintain properly aligned using a few screens with reticles and a standard video camera looking at them. This technique is used for uncritical alignment steps at PHELIX and shows good results while its implementation is very cost effective.

### 3.5. Frequency doubling and high-energy amplifier

A large part of the experimental program relies on the conversion of laser light into x-ray radiation, for which frequency doubling is greatly beneficial. In addition, frequency doubling protects the laser against back-reflection. In order to avoid a complicated pencil beam calculation and reduce risks, the frequency doubling will be done right after the high-energy amplifier.

This high-energy amplifier is the main development part of the project. Currently, there are many open-questions related to the performance of this amplifier. Hence, a central goal and deliverable of the project is its development. In the following we review the main requirements for the frequency conversion and such an amplifier.

The development of a high-energy high average power amplifier is a part of the project, to which German universities and external partners have decided to contribute. With existing laser technology based on glass amplifiers like that of PHELIX amplifiers, one would have no problem delivering the existing energy. For compactness reasons, it is advantageous to use a multipass geometry similar to the one used for the MTW laser at the university of Rochester [15, 16]. The challenge resides in the operation of this amplifier module at high shot rate. In the last years, some designs have been proposed by laboratories in the USA (University of Rochester, LLNL) and demonstrated (National Energetics [17], LLNL with Mercury) on the operation of large-aperture amplifiers under high thermal loading.

The requirement for the shot rate of the amplifier is set by the experiment shot rate in the APPA cave. This rate is limited by the accelerator on one hand and the speed at which targets will be moved from the vault into their final position. This task is fully remote controlled as no access is possible to the APPA during operation. Here the expected cycle time between shots will be 10 minutes. Therefore the laser should be able to follow this operation mode. In addition, the laser will be used for diagnostic development and based on preliminary work done at PHELIX, a shot rate on the few minute level is very comfortable. For this reason, the goal of the amplifier should be to work at a repetition rate between one shot per minute (goal) and one shot per 10 minutes (minimum requirement).

#### 3.5.1. Frequency doubling

Frequency doubling will be done using a standard KD*P crystal in type I or II. Such a KD*P crystal with type II phase-matching for ns-pulses is already in operation at PHELIX. The effective expected conversion efficiency is higher than 60% for top hat beams and can reach 80% for square pulses (in space and time).

- Beam wavefront and conversion efficiency

Conversion efficiency is strongly affected by phase-matching, which in turn is affected by the wavefront quality of the beam. In order to avoid that wavefront quality impacts the conversion efficiency, the wavefront gradient of the beam should be maintained below 0.1 mrad (in rms sense). Collimation effects are very important here and for that reason, a sensor must be implemented at this location (end-of-chain sensor) to monitor the beam quality.
Conversion efficiency of parabolic pulses

The pulses adapted to driving the shocks are pulses with a parabolic temporal shape. The following table makes an estimate of the conversion efficiency achieved when a parabolic pulse is generated. The calculation is made in the 1-D case supposing a perfect phase matching. As can be seen in the table below, the use of parabolic shape reduces the conversion efficiency by about 15%. As 80% conversion efficiency at the peak of the pulse is reasonable, an overall conversion efficiency of 60% of the module is estimated.

<table>
<thead>
<tr>
<th>Conversion efficiency</th>
<th>At peak</th>
<th>overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>62%</td>
<td></td>
</tr>
<tr>
<td>70%</td>
<td>53%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Reduction of the conversion efficiency when parabolic pulses are used.

Since good frequency conversion efficiency is desired for various pulse lengths (mostly one nominal at 100 ps and another one in the many nanosecond range), two doubling crystals will be required.

3.5.2. High-energy amplifier

The amplifier is based on a large-aperture slab amplifier that can operate at high repetition rates. The favored design relies on amplifier slabs that are actively cooled. Because the slabs have a relatively low gain, the slabs must be multi-passed. The requirements for the gain come from the specification of the output energy of the front end module and required output energy. Supposing 10% losses in the transport beam line ($T_{transport}$) and a conversion efficiency $\rho$ of 60%, the amplifier output energy $E_{MA}$ is then defined as:

$$E_{MA} = \frac{E_{TCC}}{\rho T_{transport}}$$

where $E_{TCC}$ is the energy required in the target chamber. For an output energy of 100 J, the amplifier output $E_{MA}$ must be equal to 185 J.

- Amplifier gain

It is interesting to relate the energy requirement to the expected gain in the amplifier. Here one can assume the output energy of the pre-amplifier at 20 J and a coupling efficiency of 80%, that is 16 J effectively coupled to the amplifier. That means the gain of the amplifier should be about 12.

If one assumes a single-pass geometry, a simple one-dimensional model based on the Frantz-Nodvik equation allows to give an estimate of the number of amplification steps necessary. This is shown in the table below with the goal values for the amplifier of gain of 1.5 with 4% losses between amplifiers.

One of the possible geometries uses two amplifier modules in a row and a beam that passes the amplifiers at 4 different locations across the amplifier aperture. With a beam of 12 cm diameter, a full aperture of the amplifier of 32 cm +/- 0.5 cm is necessary. This aperture is compatible with the existing PHELIIX amplifiers that can be used in a preliminary version of the laser.
A second option for the amplifier is the use of a single module that is going to be passed eight times. As it is not efficient to spatially multiplex the beam 8 times across the amplifier aperture, 4 passes with a beam of identical diameter will be used, after which the beam is retro-reflected into the amplifier for the last 4 passes. At the exit of the amplifier, the beam is separated from the input beam using a Faraday rotator. The advantage of this approach is clearly its cost, but it is technically more complicated and for this reason it is not the favored option.

A precise simulation of the beam propagation in the amplifier is going to be necessary in the early stage of the project. For this the Miro™ software developed by CEA and available at GSI can provide the necessary tool to perform this task.

### 3.5.3. High repetition rate amplifier

For the laser amplifier, an amplifier with an aperture of 32 cm should be built. The realization could be either done by a third party (vendor) or in collaboration with research groups in Europe. The development of such an amplifier may appear significant. However, we expect that such an amplification module could find applications at other facilities like ELI, HIBEF at the XFEL and more directly the Helmholtz Beamline project at FAIR. The laser will be used as a testbed for instance to gather feedback on such an amplifier before proposing the final design of the Helmholtz Beamline for FAIR.

<table>
<thead>
<tr>
<th>Gain</th>
<th>1.40</th>
<th>1.45</th>
<th>1.50</th>
<th>1.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>transmission 1 module</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>input energy (J)</td>
<td>16.00</td>
<td>16.00</td>
<td>16.00</td>
<td>16.00</td>
</tr>
<tr>
<td>input fluence (J/cm^2)</td>
<td>0.2358</td>
<td>0.2358</td>
<td>0.2358</td>
<td>0.2358</td>
</tr>
<tr>
<td>fluence pass 4 (J/cm^2)</td>
<td>0.7214</td>
<td>0.8200</td>
<td>0.9267</td>
<td>1.1646</td>
</tr>
<tr>
<td>energy pass 4 (J)</td>
<td>46.9933</td>
<td>53.4183</td>
<td>60.3709</td>
<td>75.8676</td>
</tr>
<tr>
<td>fluence pass 8 (J/cm^2)</td>
<td>1.9771</td>
<td>2.4540</td>
<td><strong>2.9895</strong></td>
<td>4.2120</td>
</tr>
<tr>
<td>energy pass 8 (J)</td>
<td>128.7957</td>
<td>159.8607</td>
<td><strong>194.7478</strong></td>
<td>274.3866</td>
</tr>
</tbody>
</table>

Table 4: Amplifier output energy after 4 and 8 passes as a function of the single pass small signal gain. The beam used in the simulation has a radius of 6 cm and a fill factor of 60%. The values are given for the peak fluence so they are slightly pessimistic (stronger saturation). For the simulation a loss in energy equivalent to the second line is taken.
One important aspect is the availability of laser glass with dimensions relevant for the amplifier. Until now, only two vendors have been able to provide such material (Schott and Hoya) but because of the manufacturing technique, on-demand melting and delivery of laser glass has only been achieved by projects with high volume requirements like the NIF and LMJ laser projects. However, in the last years a third vendor based in China is offering laser glass in dimensions and volumes compatible with this project. Some contacts have been taken and glass samples are being tested at GSI.

In addition to the availability of the raw material, polishing of the slab will be important and presents a new challenge. In the current amplifier concepts, three slabs with internal cooling are used in place of the standard 50 mm thick slabs of un-cooled amplifiers. This logically increases the requirement on the polishing precision of the glass. The use of coolant also requires the glass slabs to be coated with a coating that protects the chemically soft phosphate glass from chemical reaction.

The coolant is another area of development as the requirement for the properties of this coolant are manifold. The coolant must have a reasonable heat capacity and index of refraction close to that of phosphate glass to release the requirements on the polishing precision of the slabs. It must also be inert against the glass, have a high transmission at the emission wavelength of the laser and should be inert against insolation by the flash lamps. Unfortunately, Xenon flash lamps have an emission spectrum which is going from the UV into the near infrared. Additional filters must be probably used to reduce the amount of emission of UV from the flash lamps. And last, the coolant must allow a laminar flow.

Power conditioning is a second aspect for the project. Currently, the technology used at PHELIX and GSI relies on the concepts used by the Nova laser and exploits mercury-based ignitrons. These switches have been replaced in more modern lasers by solid-state switches that represent lower operation risks. Here a strong interest lies in the community to develop high-voltage power conditioning units suitable for our application. Expertise exists across Europe in France and in the UK and contacts have been taken with these groups. Such a development would also benefit the existing PHELIX facility that could also be used.
as a test-bed to help mitigate risks. At PHELIX the high-voltage room offers the necessary laboratory environment for such a development for instance.

3.5.1. Large-aperture amplifier as multipass amplifier

A large-aperture amplifier is for this laser not 100% necessary and probably not the most cost-effective solution for obtaining 200 J. However, the goal is clearly here to develop and test ion a real working environment an amplifier module that can be used at other facilities and in particular for the high-energy short pulse beamline planed at FAIR.

One important advantage of this amplifier is its compactness and versatility. The whole amplifier has a 4 x 1.5 m² footprint as it can be seen in Figure 15, and consists in its baseline version of 4 passes in two amplifier modules. For the start version of the laser, the amplification modules will be the amplification modules used at the PHELIX facility. This enables a considerable reduction of the risk of the project as all components in phase one are either PHELIX components or components with a high visibility and a low technical risk. In a second phase, the amplifier modules will be upgraded to actively cooled amplifiers on a one-to-one exchange basis.

![Figure 15: schematic view of the main amplifier](image)

The amplifiers sit on a metallic structure that also hosts the two telescopes necessary for image-relaying the beam. The amplifier can be adjusted in tip-tilt and transversally fined positioned into the beam. The beam that comes out of the pre-amplifier has its image after the first pass in the amplifier. A roof mirror is used to reflect the beam horizontally into the amplifier for the second pass. The beam is then sent to the first main amplifier telescope. After the telescope, the beam height is changed with a 90°-periscope arrangement and the polarization changed back to horizontal with a \(\lambda/2\) waveplate. The beam proceeds then to pass 3 and 4 on the upper range of the amplifier aperture. Here the image plane is laying between passes 3 and 4 such that a second telescope is necessary to image-relay the beam outside the main amplifier.
With this arrangement, the beam is fully image relayed through-out the pre-amplifier and main amplifier sections. Because of the mechanical constraint, the telescope is not using the standard 4-f arrangement but a more sophisticated 4 lens arrangement which enables:

- The folding of the beam and at the same time to fulfill the image relaying conditions,
- Correction of the spherical aberration and
- Exact positioning of the ghost foci outside of danger zones (in the amplifier glass or on mirror surface for instance.)

3.6. Low energy part of the system

3.6.1. Output specifications

In order to reduce cost and risk, the low energy part of the system is based on existing technology at GSI. For this an improved copy of the PHELIX programmable nanosecond front-end and pre-amplifier is proposed.

<table>
<thead>
<tr>
<th>Output energy</th>
<th>Pulse shaping</th>
<th>Beam shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 J</td>
<td>yes</td>
<td>Round, top hat, fill factor &gt; 65%</td>
</tr>
</tbody>
</table>

Table 5: Output specification of the existing nanosecond PHELIX front-end.

3.6.2. System Layout

For the first part of the system a fiber-based solution is proposed which is currently already in use at PHELIX as shown in Figure 16. This type of front end is also commercially available. As an example, a commercial system from Photline is currently being evaluated at GSI. It allows for arbitrary pulse shapes with durations from 180 ps – 15 ns, which will be controlled using a programmable arbitrary waveform generator from Kentech Instruments. This device has a signal bandwidth of 8 GHz, which is sufficient for the shortest proposed pulse duration. With up to 280 sample points and a vertical dynamic range of 12 bits a precise control of requested pulse shapes is possible. In addition, a very low time jitter of <25 ps will be sufficient for the proposed experiments. In addition, shorter pulses could be created with the help of a gate-only electric pulse driver (without shaping) to achieve 100 ps short pulses. For the proposed system laser, the fiber system presented above which delivers output energies of up to 3.5 nJ at an adjustable repetition rate (from single shot to many Hz) is sufficient.
Following the fiber system, a free-space regenerative Nd:glass ring amplifier will boost the pulse energy to 25 mJ. The amplifier will be pumped either with flashlamp or laser diodes. For the amplification of pulses with durations up to 20 ns the resonator length must be around 8 m. Such an amplifier based on a degenerate laser ring cavity is in operation at PHELIX since more than 10 years where it turned out to be very stable and reliable. A possible alternative is to use a highly-mode selective linear cavity similar to the cavity of [12]. The exact layout of the regenerative amplifier is still being worked out and is part of the early deliverables of the project.

The preamplifier will allow for output pulse energies of up to 20 J at a repetition rate of 1 shot / 45 s. Based on the experience at PHELIX this amplifier system will consist of two flashlamp-pumped Nd:glass rod amplifier heads with diameters of 19 mm and 45 mm. A prototype for a 45-mm amplifier module to be operated at high repetition rate is currently tested in detail at PHELIX (see Figure 17). This amplifier head is driven by a commercial power conditioning unit working at low voltage. For a capacitor bank voltage of 2 kV, a small signal gain of 5.6 (+/-)0.3 is achieved. In addition the evolution of the thermal lens and the formation of a steady state at repetition rates of 1 shot / 10s has been has been studied, which gives a good estimation of the necessary performance of the adaptive optics.

![Figure 17: Test setup of the 45mm laser amplifier.](image)

The energy of the preamplifier has been estimated with a 1-dimensional simulation taking into account saturation effects. The beam is assumed to be a truncated Gaussian with a fill factor of 0.4 in the first head that has a small signal gain of 10. Because of the radial gain, the fill factor will be improved to 0.6 in the second head which is simulated with a small signal gain of 4.5. As shown in Table 6, an output energy of 20 J is well within reach of this amplifier. The limiting factor is rather the fluence seen at the end of the amplifier. This value is about 3 times higher than the conservative values used at PHELIX. For the simulation a beam diameter (1% cutoff) of 15 and 40 mm respectively is assumed.
The foreseen layout of the pre-amplifier can be seen in Figure 18. The beam is delivered after the serrated aperture and fully image- relayed throughout the amplifier. The amplifier has been built such as to mitigate thermal-stress-induced birefringence effects. At the foreseen repetition rate, a strong thermal birefringence must be taken into account. In order to handle it, the amplifier heads would be used in double-pass configuration with birefringence compensation using Faraday rotators in combination with adaptive optics (see Figure 18).

Figure 18: Schematic layout of the double-pass pre amplifier.

A preliminary opto-mechanical layout has already been worked out which will replace the existing PHELIX preamplifier in the coming year (see Figure 19).
3.7. Control system

There exist a lot of integrated control systems dedicated to running shot procedures and control alignment of laser systems. A possible control-system architecture is the CS framework [18] developed at GSI. This control system is LabVIEW™ based and maintained by GSI. An implementation of the CS framework can be found at PHELIX (PCS) where the necessary tools for controlling lasers (cameras, mirrors, detectors, shot sequencer, vacuum controls) and more general tools like database logging and retrieval already exist. An alternative can be the CS++ [19], the successor of CS, which is built on native LabVIEW classes, and gains profit from the development environment and the community. The main development tasks for the new implementation of the CS framework will be:

- Safety system definition and integration (specific to the building)
- Shot sequence control and safety of the large amplifier
- Beamline supervision

3.8. Timing system

The timing system is the part of the laser that controls the shot sequence and coordinates the delivery of the laser pulse to the experiment. Particular aspects to this system are:

- The operation of the periodic part of the laser, its Frontend for instance but also the high-energy amplifiers that are likely to operate under thermal load at their own repetition rate and,
- The synchronization with the single ion bunch from SIS100.

To perform these tasks, the timing system must enable the precisely synchronized delivery of the laser and ion pulses which have to interact at the target chamber at the time T. Since the shortest ion pulse length is planned to be 50 ns and the laser pulse length to be 100 ps or longer, the jitter should be in the order of 100 ps.
The Frontend and each amplifier stage of a flash lamp pumped laser system typically requires two less critical signals: One to start the charging process of the capacitors, and a later one to flash the lamps. This second signal has to be more precise than the first in order to guarantee high reproducibility of the gain. The required accuracy scales more or less with the repetition rate of the stage. For the planned system, one has to take into account that the Frontend as well as the Preamplifier have to be operated periodically to stay in thermal equilibrium. The applied frequency must be constant to a level of 10% only. When the pump energy is delivered by pulsed laser diodes like foreseen for the regenerative amplifier, the timing scheme is simpler and reduced to the “diode on” trigger signal.

The precise timing of the laser pulse is ensured by switching Pockels cells which act as Q-switches or gates. These signals have to be delivered between 0 and 200 µs before T and with a jitter of less than 100 ps as mentioned before (in the following this is described by T – 200 µs ± 100 ps).

Figure 20 shows a possible schematic of the timing system. All time values indicated are giving an idea of their order of magnitude but they must be fine-tuned on a level given by the acceptable accuracy. For the Frontend as well as the two amplifier stages, one can find the time before T when the charging (“Charge”) and the ignition (“Igni”) signal of the capacitor circuits have to be delivered.

The system is fully controlled by timing signals originated by the accelerator. The “working horse” is a periodic signal delivered each 50 s (0.02 Hz). It is directly used to operate the Preamplifier and shall arrive about 1 ms before T. To ensure this, the ions bunch can be re-bunched in the SIS 100 if this leads to a frequency change not higher than 5 Hz.
From this 0.02 Hz signal, the slow signals for the Frontend are derived by splitter and delay generators. For charging and ignition the main-amplifier stage, the accelerator has to deliver a “one after the next”-Signal two 0.02 Hz-beats before T. This rather long time can be used by the accelerator to re-bunch the ions in order to ensure that the very last 0.02 Hz-beat before T is within the wanted time window of 10 µs.

At the very end of this sequence, finally a very precise signal must be delivered about 200 µs ± 100ps before T. This is used to switch the Pockels cells (“PC”) for this special pulse which will be amplified in the laser chain and interact with the ions.

All hardware necessary to provide the signals on the laser side is available and in use at PHELIX. Of course, the timing system will be much larger than this described above since there shall be the possibility to switch between a periodic alignment and the shot mode in order to switch detectors as cameras for each pulse or only once at the right time. It might also be necessary to synchronize this laser with others which might be setup in the future. But all this type of questions are solved at PHELIX (with two independent frontends) and rhelix which can be operated in parallel and within an accuracy of better than 100 ps related to the ion micro bunches of the UNILAC.

On the accelerator side, a complication occurs from the fact that nothing is running strictly periodically any more as, for example, in case of the UNILAC. Of course, the ion bunch position is well controlled and actively corrected at any time inside the SIS 100 which is of elementary interest for “kicking” it out to reach the experimental area. But so far, it seems not to be of interest for other typical accelerator experiments to know the time when the ions exactly will arrive at a target chamber in advance nor to synchronize this with any periodic signal. But is seems to be feasible to create the necessary signals by use of the “White Rabbit“-System (at least the periodic and the signal long before T) while the very precise signal might be created by use of the “White Rabbit” in combination with the BUTIS-System planned for FAIR. These details still have to be examined.

### 3.9. Wavefront budget and wavefront control

The wavefront requirement does not come from the proposed experiments that can work with a loose focusing but from the necessity to achieve a good frequency conversion efficiency. If the system achieves about one wave peak-to-valley of wavefront distortion, this goal will be met.

#### 3.9.1. Operation of large-aperture amplifiers

The proposed laser aims at operating glass amplifiers at high repetition rates. In the final version of the laser, the amplification medium will not cool down completely between shots and therefore the operation of the laser under thermal loading must be controlled.

From our experience with PHELIX or other systems, it is possible splitting the wavefront aberrations in three categories that can be addressed separately from a procedure and system stand point. These three aberrations are:

- The static aberration: this aberration comes from both imperfections in the polishing of the components and alignment mistakes as well as component deformations due to non force-free mounting. It is possible to limit the imperfections of the optical elements by specifying ultra-high
polish quality but the cost is usually prohibitive for a system including large amounts of elements (e.g. the described preamplifier system contains of more than 50 optical surfaces).

- The on-shot aberration: when the pumping energy is not deposited uniformly in the amplifier, the local heat deposition and the corresponding instantaneous temperature increase is not uniform, yielding change in the index of refraction and wavefront distortion. This is in particular true in rods that have a strong radial gain non-uniformity.

- The thermal aberration: when the repetition rate is higher than the cool-down time of the amplifier, the temperature of the amplifier increases with time. This is the thermal load.

The first two aberrations are being handled in the following way: first a passive wavefront budget is being determined for the whole system. The wavefront budget is determined from the realistic characteristics of the optical elements to be used. Then alignment procedures are worked-out to minimize the aberration induced by misalignments. Because of the complexity of modern laser systems, these first two steps lead to a residual static aberration of the order of magnitude of one to a few waves peak-to-valley. Adaptive optics techniques are added to bring the aberration a factor of 10 lower. In our case, this will be done using a deformable mirror. The on-shot aberration is in principle handled by the same system too. The reason for that is that the dynamic range of the deformable mirror used for the static correction has in general enough dynamic range to address both and this aberration is very deterministic if the system is used in constant conditions. As it turns out, the most dominant part of the on-shot aberrations is ‘defocus’. Hence, the amount of on-shot aberrations to be compensated by the deformable mirror can be further reduced employing a movable lens at one of the relay-imaging telescopes. We have demonstrated this control at PHELIX in the last years and will use the same technique for the proposed laser.

The thermal aberration is more challenging and as a consequence no high-energy laser in the world works under thermal load to our knowledge. Instead, one waits until the amplifiers are cooled down. In any case, the amplifier cannot work under very high thermal load. Based on preliminary tests done at PHELIX on rod amplifiers, an increase of the repetition rate by a factor of 10 compared to the cool down time of the amplifier is the maximum one can achieve. Since our ultimate repetition rate goal is 1 shot per minute, the cool down time of the amplifiers must be around 10 minutes. In other words, for the lower repetition rate of 1 shot/10 min, the system is supposed to have relaxed to it cold state and the thermal load on the wavefront budget will be negligible (residual thermal aberration lower than \(\lambda/4\) peak-to-valley).

This goal is not achieved by the current PHELIX amplifiers which have a cool down time of 90 minutes. This is on the contrary the primary goal in the dimensioning of the cooling scheme. A technical study will be made at the beginning of the project to assess of this effect that will determine the number of slabs and their thickness.

For the higher shot rate, a significant pile up of thermal aberration is expected to happen and must be taken into account. From shot data gathered at PHELIX on cylindrical systems (rods) we expect however that we can compensate the thermal aberration at a repetition rate 10 times higher than the repetition rate that induces no thermal load.

3.9.2. Equipment necessary
Standard wavefront control devices have been available on the market for the last ten years. These devices rely on a thin mirror whose surface can be shaped to via piezo or mechanical actuators introduce the desired wavefront compensation to the beam. A possible solution for such a device is shown in the Figure 21.

![Example of 100-mm deformable mirror from the firm ISP (model MD-100-C-52)](image)

The deformable mirror is usually built in a closed loop where its operation has to be controlled locally via a wavefront sensor as well as at the point in the system where the wavefront must be corrected. Because of this somehow distributed architecture across the laser, a fully embedded system is highly-desirable.

The measurement equipment could be based on Shack-Hartmann sensors. GSI has developed its own hardware and analysis software that is compatible with the CS framework and PCS such that the measurement devices can be distributed across the laser system. Such a system can be fully embedded in any other control system too. Because the cost of the equipment is reduced to the cost of a standard camera and a relatively cost-effective multi-lens array, a very low cost per device can be reached.

### 3.9.3. Requirements and wavefront budget

To ensure a good start point, all optics will be specified per default with a transmitted wavefront aberration of $\lambda/10$ (peak-to-valley) in the laser chain from the initial image plane to the laser output. This requirement is tight for standard optical components but realistic. For more complicated elements, a transmitted wavefront of $\lambda/4$ (peak-to-valley) could be tolerated but the number of these components should not exceed 16. This will be reserved to the complicated main amplifier components. A rough estimate of the number of optical elements then yields a static wavefront that should not exceed 2 waves.

To make the system manageable, the thermal aberration of the main amplifier should be less than $\lambda/4$ at 1 shot per 10 min.

### 4. References

[18] the CS framework is an open source software https://sourceforge.net/projects/cs-framework