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**Doctoral School of Laser and Accelerator Engineering and
Applications**

Ph.D. THESIS Summary

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**INVESTIGAREA SI REDUCEREA RETRO-
REFLEXIEI IN SISTEME LASER DE PUTERI MARI**

**INVESTIGATION AND MITIGATION OF BACK-
REFLECTION IN HIGH POWER LASER SYSTEMS**

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Introduction

The advent of the Chirped Pulse Amplification¹ (CPA) technique occurred in 1985, has revolutionized the field of laser physics, allowing for the generation of ultra-high-power laser pulses. These advancements have propelled the creation of increasingly powerful laser facilities, capable of generating extreme peak powers and driving new experiments across a variety of scientific domains. Prior to CPA, laser power was severely limited by the risk of damaging amplification materials. Early systems, operating without CPA, were only able to achieve powers on the order of gigawatts (GW) in the 1960s and 1970s. In the CPA process, a broadband pulse is generated in an oscillator, and then stretched using an optical stretcher, which typically consists of diffraction gratings. By temporally stretching the pulse prior to amplification and then compressing it after, CPA enables the safe amplification of femtosecond-scale pulses to the petawatt^{2,3} (PW) level without inducing optical degradation. This is possible because the acceptable fluence on optical components is inversely related to the duration of the laser pulse, meaning that longer pulses can tolerate higher fluence levels without damaging the optics, as the energy is distributed over a much longer time while also reducing the risk of thermal or mechanical shocks:

$$F_{\text{th}}(\tau) \propto \sqrt{\tau} \quad (1)$$

This relationship holds reasonably well from the nanosecond regime down to a few picoseconds. Assuming a representative value of $F_{\text{th}} = 10 \text{ J cm}^{-2}$ at $\tau = 1 \text{ ns}$ for a broadband (50 nm) high-quality dielectric mirror, this scaling predicts thresholds of approximately 0.32 J cm^{-2} at 1 ps and 0.1 J cm^{-2} at 100 fs pulse durations.

CPA opened the door to a vast array of applications in science, including strong-field physics⁴, relativistic optics, and plasma physics. Examples of laser systems that have utilized CPA to reach unprecedented power levels include the Titan laser at Lawrence Livermore National Laboratory^{5,6}, capable of generating 0.3 PW, and the Vulcan laser at the Rutherford Appleton Laboratory⁷, reaching 1 PW. These systems are foundational to the exploration of relativistic laser-matter interactions. At the forefront of high-power laser development stands the Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility, which houses a 10 PW laser system, the most powerful lasers ever built. This system, capable of delivering 240 J in 24-fs pulses⁸, employs a hybrid Optical Parametric Chirped Pulse Amplification (OPCPA) combined with traditional CPA. The sheer power and precision of ELI-NP have enabled groundbreaking research in areas such as laser-driven particle acceleration⁹, protons, electron and positron acceleration, ion acceleration, radiation pressure acceleration (RPA), target normal sheath acceleration (TNSA), as well as laser Wakefield acceleration. The capabilities of multi-petawatt (multi-PW) lasers like ELI-NP¹⁰⁻¹⁵ provide unprecedented access to relativistic and quantum regimes of laser-matter interactions.

This thesis investigates the issue of back-reflection in the context of CPA–OPCPA hybrid laser architecture, employing Titanium-Sapphire (Ti: Sa) solid-state amplifiers. The system under study is capable of delivering multi-petawatt (PW) peak powers in ultrashort pulses lasting only a few tens of femtoseconds. While such performance is essential for exploring high-intensity regimes, it also significantly increases the risk of detrimental back-reflections from targets on optical components. These back-reflected signals can introduce a range of issues, including unwanted EMP “noise” and even permanent damage to sensitive elements within the amplification chain.

The core objective of this work is to characterize the mechanisms of laser back-scattering under high-intensity irradiation and to identify effective strategies for its mitigation. This includes a combination of experimental diagnostics, numerical modeling, and the evaluation of passive and active protective measures. The ultimate goal is to enhance the operational safety and stability of multi-PW laser systems by reducing the impact of unwanted back-reflected light. Through this investigation, the thesis contributes to the broader effort of optimizing ultrafast, high-power laser infrastructures for reliable and repeatable performance in demanding experimental settings. This study was motivated by the real issues encountered in the High-Power Laser System (HPLS) at ELI-NP, where several instances of damage were caused by back-reflections from solid targets. As extreme intensities are rapidly applied on target surface, ionization occurs on a sub-cycle timescale through field-ionization mechanisms, such as multiphoton and tunneling ionization, followed by rapid collisional and impact ionization. As bound electrons are liberated, the initially solid material is converted almost instantaneously into a dense plasma. The plasma frequency governs the dielectric response of the medium and therefore its refractive index. Once $\omega_p > \omega$, the plasma becomes overdense, the remaining portion of the incident pulse is predominantly redirected rather than transmitted. The steep density gradient at the plasma boundary leads to strong reflection and refraction, with angular distribution determined by the evolving plasma profile. By exploring the relationship between laser parameters and target response, this research will contribute to the development of improved strategies for preventing back-reflection, thereby ensuring the safe and effective operation of multi-PW laser systems in the future.

During the commissioning experiments utilizing the 10 PW laser, dozens of both solid and gaseous targets have been irradiated. Analyzing the BR signal revealed a clear distinction between these two target types in terms of energy return. In gaseous targets, while the BR signal is still observed, it is generally significantly weaker and typically does not reach the laser bay. This is most likely due to a loss in coherence and scattering processes occurring during the generation of the BR light. In simple terms, in the particular case of gaseous versus solid targets, the definition laser-matter interaction is an overgeneralization; comparing gaseous and solid targets under high-power laser irradiation is analogous to comparing a car transferring energy through stochastic interactions with air resistance versus crashing into a solid wall. The gaseous medium, while reactive, offers a diffuse and gradual exchange of energy, whereas a

solid target, defined by a sharp and well-structured media interface, produces a far more abrupt and “eventful” interaction. It is this abruptness and clear media boundary that makes solid targets significantly more sensitive to laser beam properties and more susceptible to generating parasitic effects such as BR. This distinction is fundamental, and accordingly, solid targets are of particular interest for the topic of this thesis.

Geometrical model for plasma mirror alignment

One widely used solution to this challenge is the plasma mirror (PM). A PM is a component usually used in high-intensity lasers to enhance the temporal contrast of ultrashort pulses. It operates as an intensity-dependent optical switch, being transparent or anti-reflective (AR) at low intensities ($<10^{14} \text{ W cm}^{-2}$) and highly reflective at high intensities, thus acting as an ultrafast optical gate. The operation principle depends on the nonlinear interaction between the incident laser field and a solid surface, typically with AR coating present and optimized for the spectral bandwidth of the laser pulse. At low intensities (stemming from pre-pulses, satellite pulses, or pedestal noise) the optical coating maintains its designed AR properties, allowing these low-energy components to pass through without generating any significant interaction. The main pulse, however, carries a much higher peak intensity (typically exceeding $10^{15} \text{ W cm}^{-2}$). Upon reaching this intensity threshold, the leading edge of the main pulse ionizes the surface of the plasma mirror substrate, rapidly forming an over-dense plasma layer within a few femtoseconds. This newly formed plasma possesses a critical electron density such that its refractive index becomes nearly zero for the incident wavelength, rendering the surface highly reflective due to the abrupt change in optical properties. As a result, the remainder of the high-intensity main pulse is reflected with minimal temporal delay.

In short, this is an optical element that takes advantage of the intensity-dependent reflectivity of an AR surface to suppress the prepulse and pedestal light while reflecting the high-intensity main pulse towards the target.

In this work, our aim is to streamline PM alignment by providing a set of geometrical equations to estimate the precise intensity on the PM surface based on placement and setup parameters. A rendered representation of experimental geometry is represented in Figure 1. By incorporating key factors such as beam diameter, pulse power, and off-axis parabolic (OAP) mirror geometry, we conceived a generalized geometrical model designed to offer practical guidelines for optimizing PM performance in high-power laser systems.

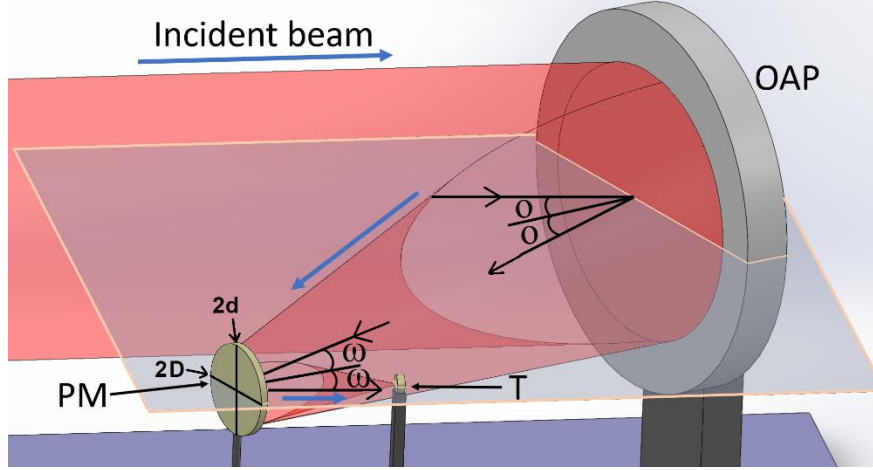


Figure 1 Rendered representation of the experimental setup. The incoming collimated beam is reflected off the OAP and focused onto the target via the PM. The minor and major axes of the ellipsoidal beam profile formed on the PM are denoted by d and D , respectively. The horizontal plane containing the OAP and PM half angles (i.e. $\hat{\theta}$ and $\hat{\omega}$, respectively) is highlighted and will be later utilized in Figure 2 to determine the theoretical model

Theoretical Model

The development of an accurate geometrical model for PM placement requires a comprehensive analysis of all factors influencing the beam's interaction with the PM surface. A crucial parameter is the half-angle of the OAP relative to the incident beam, denoted as $\hat{\theta}$, which governs how the laser beam is distributed onto its surface. A larger OAP angle results in a longer ellipsoidal distribution, influencing the geometrical model, as shown in Fig. 1. This theoretical model assumes that the angles $\hat{\theta}$ and $\hat{\omega}$ are contained within the same plane, which is a common experimental geometry.

In the following, the curvature of the OAP is neglected and we approximate the OAP paraboloid with a plane. The angle $\hat{\omega}$ generates its own ellipsoidal projection onto the PM within the same plane. To account for these geometric features, we divide our calculations into two components: the minor and major axes of the ellipsoidal beam profile on the PM surface, which are the two values needed to determine the surface S .

$$S = \pi \cdot d \cdot D \quad (2)$$

where d and D are the radii corresponding to the minor and major axis of the ellipse, respectively. The minor axis $2d$ is independent of both the angles $\hat{\theta}$ and $\hat{\omega}$. It depends solely on the distance x from the focal point, the effective focal length f , and the initial diameter of the laser beam Φ . This axis is determined by straightforward geometrical relationships involving these parameters as follows:

$$d = \frac{\Phi \cdot x}{2f} \quad (0)$$

The major axis $2D$, in contrast, is influenced by the entire set of parameters, including both $\hat{o}$ and $\hat{\omega}$. It is asymmetrical with respect to the central axis of beam propagation when $\hat{o}$ and $\hat{\omega}$ differ. To calculate it, we split it across the beam's central axis, and break it into two geometric problems, solving for the length of segments i and j :

$$D = \frac{i + j}{2} \quad (4)$$

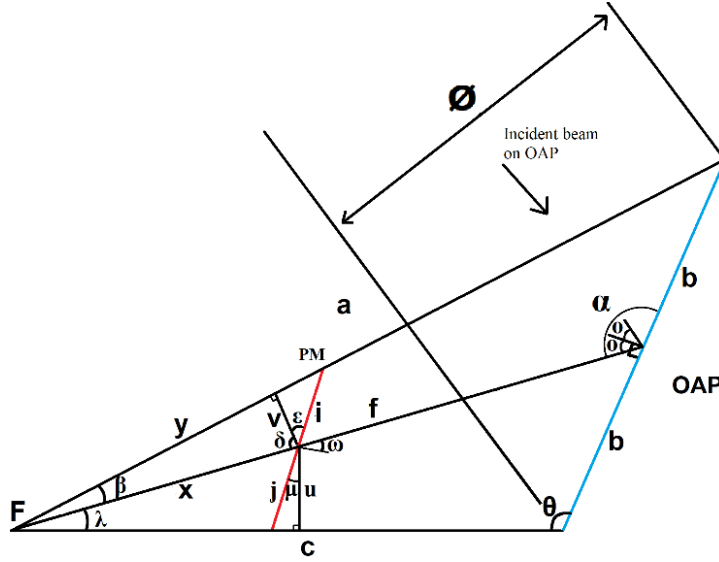


Figure 2 Geometrical model depicting the horizontal plane of major axis. Φ is the incident beam diameter on the OAP, PM is situated at a distance x from focal point F which is the position of the target. The effective focal length of OAP is f . The width of the incident laser spot on the OAP is $2b$.

A detailed geometrical model of the major axis and its dependencies is shown in Figure 2. Here, the OAP and PM are represented by straight blue and red lines, respectively. Additionally, the beam's trajectory following its interaction with the PM is shown behind the mirror, which is a standard representation in geometrical optics involving reflective surfaces. Based on diameter Φ and $\hat{o}$ we determine the projection of the beam onto the OAP.

$$b = \frac{\Phi}{2 \cos(\hat{o})} \quad (5)$$

From f , b , and $\hat{\alpha}$ ($\hat{\alpha} = 90^\circ + \hat{o}$) we apply the cosine law to obtain the distance a :

$$a = [f^2 + b^2 - 2bf \cos(90^\circ + \hat{o})]^{1/2} \quad (6)$$

Given that all sides a , b and f are known, we can now solve for $\hat{\beta}$ utilizing again the cosine law:

$$\cos(\hat{\beta}) = \frac{a^2 + f^2 - b^2}{2af} \quad (7)$$

To aid in solving for i , we trace a line v from the intersection point between the PM and the beam central axis perpendicular to the side a . We employ this auxiliary geometrical construct which creates a right triangle with the sides x , y and v , needed to create relationships from the known input parameters: v can be easily deduced ($v = x \sin \hat{\beta}$), as well as the newly generated angle $\hat{\epsilon}$ ($\hat{\epsilon} = 90^\circ + \hat{\omega} - \hat{\delta}$, where $\hat{\delta} = 90^\circ - \hat{\beta}$). Now we can solve for i ($i = v / \cos \hat{\epsilon}$) and conclude the first half of the problem. Similarly to i , we can calculate j and having a complete knowledge of the Δabf triangle we implicitly have information regarding $\hat{\lambda}$ ($\hat{\lambda} = \hat{\alpha} - \hat{\theta}$), $\hat{\theta}$ and c :

$$c = \left\{ a^2 + 4b^2 - 4ab \cos \left[90^\circ - \arccos \left(\frac{a^2 + f^2 - b^2}{2af} \right) - 0 \right] \right\}^{1/2} \quad (8)$$

where the argument of the cosine function in the above Eq. (8) is $180^\circ - \hat{\theta} - \hat{\lambda} - \hat{\beta} = 90^\circ - \hat{\beta} - \hat{\theta}$ and $\hat{\beta}$ is obtained from Eq. (7). With the knowledge of c , we can calculate $\hat{\theta}$:

$$\hat{\theta} = \arccos \left(\frac{4b^2 + c^2 - a^2}{4cb} \right) \quad (9)$$

Tracing a line segment u from the intersection between PM and the central axis perpendicular to the side c gives a right triangle from which one can deduce u and j : $u = x \sin \hat{\lambda}$, $j = u / \cos \hat{\mu}$, where $\hat{\mu} = \hat{\epsilon} + \hat{\delta} - 90^\circ - \hat{\lambda}$ and furthermore $\hat{\mu} = 90^\circ + \hat{\theta} - \hat{\theta}$.

Building on these findings, the process of deriving a more generalized formula can be further streamlined. By incorporating all the geometric dependencies outlined above, several variables can be substituted to obtain a generalized expression for both i and j

$$i = \frac{x \sin \left[\arccos \left(\frac{a^2 + f^2 - b^2}{2af} \right) \right]}{\cos \left[\arccos \left(\frac{a^2 + f^2 - b^2}{2af} \right) + \hat{\omega} \right]} \quad (10)$$

$$j = \frac{x \sin \left[90^\circ + \hat{\theta} - \arccos \left(\frac{4b^2 + c^2 - a^2}{4bc} \right) \right]}{\cos \left[\hat{\omega} - 90^\circ - \hat{\theta} + \arccos \left(\frac{4b^2 + c^2 - a^2}{4bc} \right) \right]} \quad (11)$$

We also know the dependency between area S , laser power P and laser intensity I , where $S = P/I$. As such, we can enunciate a generalized formula for intensity on PM by replacing variables in Eq. (2):

$$\frac{P}{I} = \frac{\pi x \Phi(i + j)}{4f} \quad (12)$$

where i, j, a, b , and c are given by Eqs. (10), (11), (6), (5) and (8), respectively.

By accounting for these geometrical particularities, the proposed model provides a generalized and robust framework for optimizing plasma mirror placement in high-power laser systems.

We apply our model to the conditions and constraints of a real experimental setup that uses a 1 PW beam delivered by the HPLS at ELI-NP. In our experiment, the laser had an energy per pulse of 24 J and a pulse duration of about 24 fs. The purpose of the experimental campaign utilizing the 1 PW configuration was to irradiate different types of thin film targets for evaluating proton acceleration. The specific setup configuration presented here enabled the acceleration of protons to cut-off energies of approximately 20–30 MeV using Al and DLC foils as targets, with thicknesses ranging from 0.16 to 3 microns. By replacing the variables in the generalized model given by Eq. (12) with our experimental parameters we obtain:

$$\frac{P}{I} = 2.11 \times 10^{-3} x^2 \left[\frac{0.1264}{\cos(7.25^\circ + \omega)} + \frac{0.1409}{\cos(\omega - 8.1^\circ)} \right] \quad (13)$$

where x is given in cm. We can obtain x as a function of $\hat{\omega}$ for a specific intensity I :

$$x = \left[\frac{4.74 \times 10^2}{\left(\frac{I}{P} \right) \left[\frac{0.1264}{\cos(7.25^\circ + \omega)} + \frac{0.1409}{\cos(\omega - 8.1^\circ)} \right]} \right]^{1/2} \quad (14)$$

where the ratio I/P varies depending on the intensity on the PM ($I/P = 1$ for an intensity of $10^{15} \text{ W cm}^{-2}$). Using Eq. (13) we generate a 3D surface that highlights the dependency between intensity I , distance x , and angle $\hat{\omega}$ as shown in Figure 3.

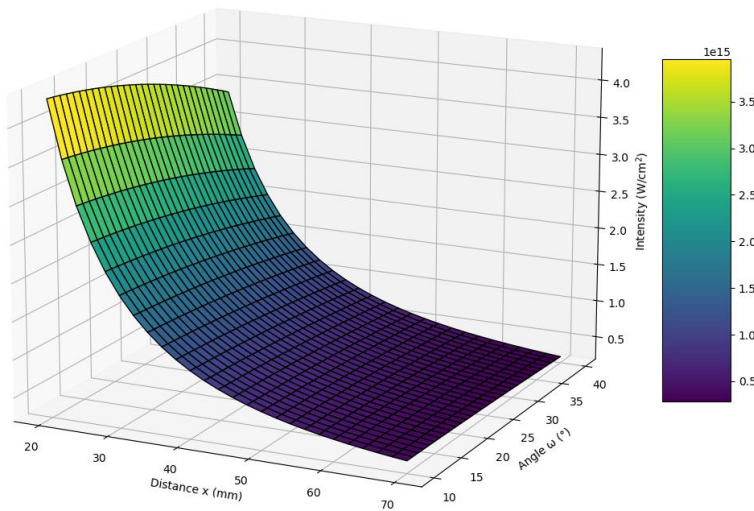


Figure 3 3D surface highlighting dependencies between intensity I on PM, position x and angle $\hat{\omega}$.

The presented maps can be used to infer the evolution of parameters between different physical experimental setups and constraints¹⁶.

In conclusion, as is the case for this work, PM are most effective in systems where ultrahigh temporal contrast is essential, such as in laser-plasma interaction experiments where even weak pre-pulses can cause premature ionization or target deformation. Their integration into multi-petawatt CPA and OPCPA-based systems as well as their precise alignment has become a standard method for preserving beam quality and ensuring clean, high-fidelity interaction with solid or structured targets.

Assessing optical damage risks by simulating the amplification of BR in a multi-PW laser system

The continuous advancements in laser science and material manufacturing have paved the way for the development of increasingly powerful laser facilities. Among these, multi-petawatt laser systems have emerged as foundational tools in modern experimental physics, necessitating ever more refined engineering, diagnostics, and predictive modeling. As these high-power systems become more sophisticated, so too does the need for robust simulation frameworks capable of accurately capturing their behavior. In this chapter, we present a computational model based on the Frantz-Nodvik formalism, developed to simulate the amplification dynamics within the HPLS architecture at ELI-NP. This framework aims to closely replicate the physical amplification process across multiple amplifiers within the system. The initial goal is to achieve accurate alignment with measured, well-characterized behaviors of the existing HPLS configuration. Once this alignment with the "known" system is validated, the framework is extended into the "unknown" by simulating its response under alternative amplification regimes and by modeling the amplification of BR signals originating from experimental targets.

At its core, the framework is driven by a Python-based simulation engine. It also incorporates an optimization algorithm to fine-tune amplifier parameters for better alignment with physical measurements, along with a simulation of BR amplification originating from experimental targets. A critical aspect of managing high-power laser systems is mitigating optical damage caused by BR or B-integral, to which optical elements operating near their damage thresholds or with AR coatings are particularly susceptible. The alternative approach described here considers the reduction of the number of PMs used, or even their elimination from the setup, making full use of the pulse's energy and of the good focus on target. In order to achieve this, one has to

mitigate the BR associated risks. This is achieved through accurate simulations of BR amplification that mitigates potential damage caused by it.

Methodology

In HPLS, the design of amplifiers considers the necessity for flexible power output, ensuring that each amplifier can deliver the required energy for achieving 100 TW and 1 PW levels on target. When operating in the full amplification regime to reach 10 PW peak power, the former amplifiers function in a reduced state, providing just enough energy to seed the next amplifier. The first advantage is avoiding seeding unnecessary high energy in subsequent amplifiers: this strategy ensures a significantly increased lifetime of dozens of optical and electrical components such as flash lamps and capacitors present mostly in pump lasers and amplification system. Another crucial advantage is decreasing the accumulated nonlinear phase shift a laser pulse experiences as it passes through a medium with a nonlinear refractive index such as the Ti: Sa crystals.

$$B = \frac{2\pi}{\lambda} \int_0^L n_2 I(z) dz \quad (15)$$

It is evident that B-integral accumulation increases linearly with laser beam intensity. A high B-integral is undesirable for a laser beam as it indicates significant nonlinear phase distortion, which can degrade beam quality, reduce focus-ability, and lead to filamentation or large-scale self-focusing. The downside of this mode of operation is lower extraction efficiency and increased residual gain (in post-pulse regime), which can enhance the amplification of the BR light from a target. This phenomenon presents a potential danger to the laser system.

In an alternative scenario, increasing the pumping of solid-state amplifiers can, somewhat counterintuitively, lead to lower gain in the post-pulse regime. This occurs due to improved extraction efficiency as the amplifiers run in a more stable, saturated regime. This reduces the amplification potential for any BR light from the target.

The Frantz-Nodvik Equation

The Frantz-Nodvik equation is a well-established model for describing the amplification of laser pulses in a gain medium. The equation takes into account the saturation of the gain medium, allowing for accurate predictions of the energy output. The Frantz-Nodvik equation is:

$$\begin{aligned} J_{out} &= J_{sat} \ln \left\{ 1 + \left[\exp \left(\frac{J_{in}}{J_{sat}} \right) - 1 \right] \exp \left(\frac{J_{stock}}{J_{sat}} \right) \right\} \\ &= J_{in} G_E \end{aligned} \quad (16)$$

J_{in} can be calculated by dividing the input (or seed) energy to the beam cross-section area: $J_{in} = E_{in}/\pi r^2$. where J_{sat} is the saturation fluence which is a property of the crystal. While for energy content it is a common practice to assign it a fix value, in a spectral treatment the J_{sat} is dependent on both the seeds wavelength and the crystal's emission cross-section as seen in Eq. (17):

$$J_{sat} = \frac{h \cdot c}{\lambda \cdot \sigma_{\lambda}} \quad (17)$$

J_{stock} represents the absorbed pump fluence which is linked to the quantum efficiency determined by the wavelength ratio between the seed λ_{in} and pump λ_p , as well as an arbitrary loss factor influenced by the crystal's absorption of the pump beam A:

$$J_{stock} = \left(A \frac{\lambda_p}{\lambda_{in}} \right) \frac{E_p}{\pi r^2} \quad (18)$$

This analysis is strictly limited to the energy domain and a potential limitation of the current methodology could be its omission of beam temporal chirp and its broad bandwidth (100 nm). To achieve a more accurate representation of a real amplifier, energy measurements were collected for each pass through the amplifier while operating it at a specific pump energy level. This provides a reference table of actual energy measurements that can be used to align our simulation. This alignment involves fine-tuning a set of amplifier parameters to ensure the simulated energies closely match the real measurements. To this end, we developed a Python script that calls Eq. (16) for each pass through the amplifier, using the known approximate input range for each parameter. The algorithm updates J_{in} and J_{stock} for each pass, as explained earlier.

By using the optimization script, we now have the specific parameters that define each amplifier in the HPLS. All the collected data are centralized and will be used to simulate the amplification of a laser beam throughout the entire HPLS. For this task, another script was developed that applies Eq. (16) pass by pass and amplifier by amplifier, accounting for gain depletion after each pass through the crystal and the progressive beam expansion as the pulse enters each new amplifier.

To enhance the framework's accuracy, we must account for a phenomenon present in Amp 1.2, thermal lensing. Pumping at high repetition rates and energy levels leads to the formation of a strong thermal lens. In the physical system, this thermal lens effect is compensated by injecting the seed with a relatively large divergence of ~ 2 mrad. This approach is effective, but spreads the seed over an area larger than the pumped region, resulting in partial clipping of the beam at each pass through the crystal.

To simulate this clipping attenuation, we calculated the thermal lens of the crystal and developed a simplified geometrical model that approximates the beam's behavior through five apertures (corresponding to five passes) as seen in Figure 5. here $\partial n / \partial T \approx 1.4 \times 10^{-5} K^{-1}$ for Ti: Sa, $k \approx 0.4 W / (m \cdot K)$, $P_{heat} \approx 100 W$ for Amp 1.2) and $f = 42 m$ for Amp 1.2 crystal lens.

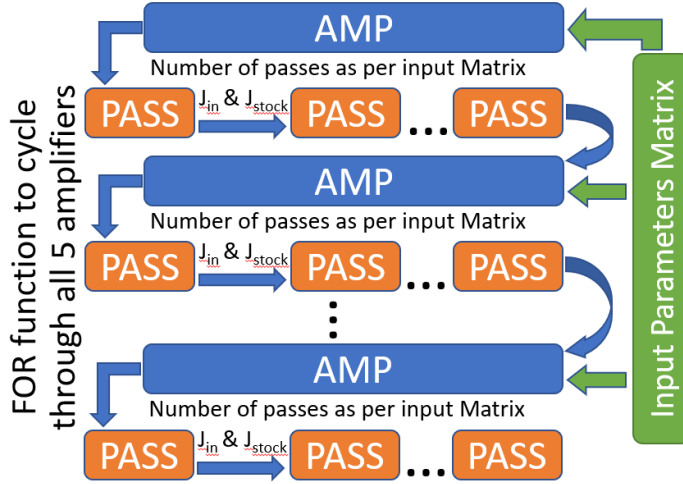


Figure 4 Logic scheme of the framework that models the amplification chain. AMP function gathers data from input matrix and calls PASS to perform the calculation.

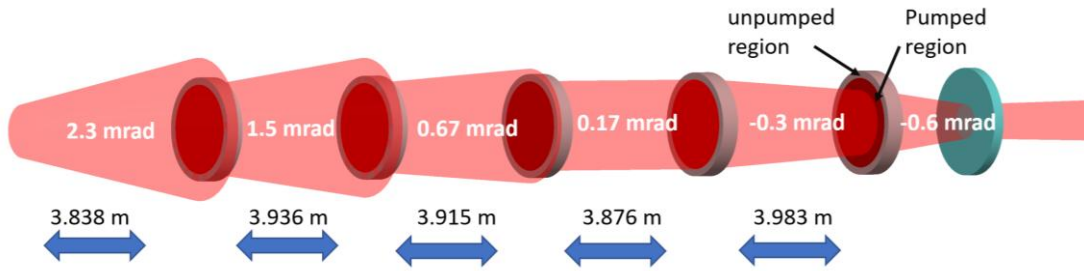


Figure 5 Simplified cross-sectional view of Amp 1.2's geometrical model, illustrating beam clipping and divergence evolution during amplification. The red area shows the pump diameter,. Calculated attenuation values for each pass are: 0.71, 0.47, 0.71, 0.95, and 1.24. Note the reduced diameter in the final pass enhances the extraction efficiency.

Given the characteristics of the beam in Amp 1.2, we approximate the evolution of the beam with a geometrical approach and neglect diffraction. By dividing the pump area by the seed area at the entrance of the crystal, we obtain our attenuation factor for each pass. This approach ensures that the simulated energy attenuation due to clipping closely matches the real behavior observed in Amp 1.2.

The last step is to deal with a particular feature present in the last 3 stages of amplification: sequential pumping. This drastically reduces the peak gain responsible for emergence of transversal lasing by extending it over the whole duration of the amplification process. To implement this in the script, we simply populate a 3×3 table with pumping energies (3 passes $\times$ 3 amplifiers) which the AMP function utilizes when encountering those specific passes.

The presented features accurately model the HPLS in energy domain and serve as a solid basis for the integration of spectral analysis. To perform a spectral evolution across the amplification chain, we feed the script with a real spectrum of the seed extracted after the DAZZLER. The spectrum is then divided into 500 slices (or narrow wavelength ranges) and fed sequentially from "Red" to "Blue" into the Eq. (16) as J_{in} while updating J_{stock} after each iteration. Moreover, by accounting for the crystal's

emission cross section for each slice we can simultaneously emulate both the red-shifting and gain-narrowing phenomena.

When all amplifiers have been accurately tuned and the amplification of the laser beam across HPLS has been simulated, we can precisely track the intensity of the laser beam to calculate the accumulated B-integral. This is achieved by implementing Eq. (15) within the amplification chain script. The laser beam's passage through the crystals is divided into 20 narrow spatial intervals for each pass to accommodate the ramp-up in intensity within the crystal. The script iterates through all intervals and multiple passes for each crystal, accounting for their specific thicknesses. In addition to calculating the contribution to B-integral from the crystals, the calculation also incorporates contributions from free propagation in air between passes and crystals, as well as from the 65 mm fused silica window used to inject the beam into the OC placed in vacuum. Together, these components complete the total B-integral calculation.

After achieving a well-fitted model, the framework was extended to simulate BR propagation and amplification produced in an experiment by the interaction of the laser pulse with a thin foil target¹⁷. This was done by seeding the beam back through the 5 amplifiers with an input energy level around hundreds of mJ, a value often observed from solid targets during the 10 PW experimental campaign utilizing our custom diagnostic devices built to capture BR. When estimating the residual gain, we must account for gain decay, which takes place during the beam's round-trip travel from the crystal to the target and back. From the fluorescence lifetime of the Ti: Sa crystal $\tau = 3.2 \mu\text{s}$ we can fit the delay as a gain loss. By sequentially seeding each amplifier with the output of the previous one, we can map the energy levels across the HPLS components as a function of BR percentage as shown in Figure 6.

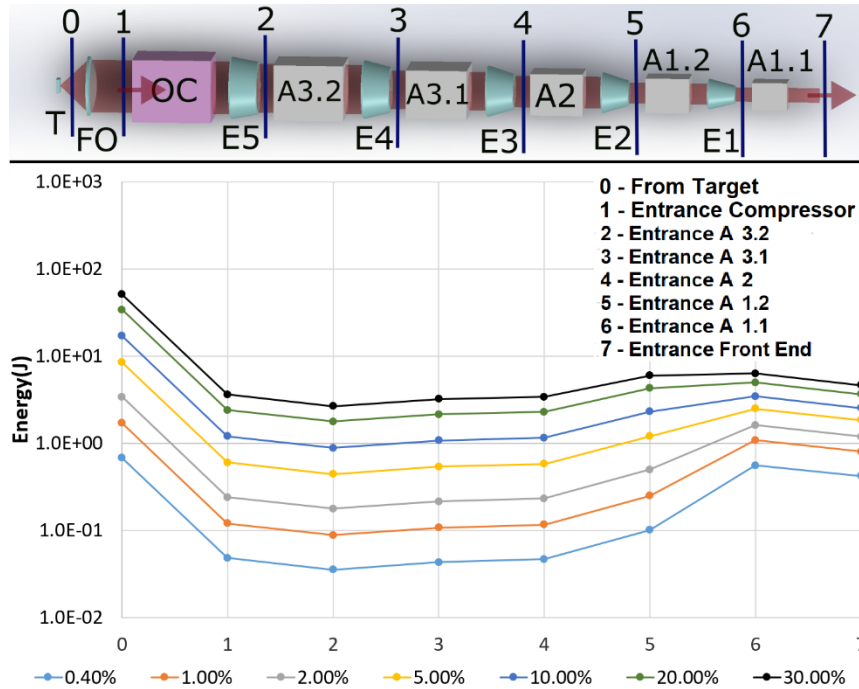


Figure 6 Simulation of the BR energy amplification in the HPLS for BR factors ranging from 0.4% to 30% off target at 10 PW laser power level. The energy is tracked across key locations 0 to 7 in the HPLS. Note that the sudden energy drop at

location 1 is due to low reflectivity of damaged PM. The labels stand for *T* – Target, *FO* – Focusing Optics, *OC* – Optical Compressor, *E1*, *E2*, *E3*, *E4*, *E5* – Beam Expanders, *A1.1*, *A1.2*, *A2*, *A3.1* and *A3.2* – Amplifiers composing the amplification chain.

As seen in Figure 6, there is sufficient gain to maintain the pulse’s energy across the system. In an attempt to reduce this BR amplification cascade while exploiting the advantages of reduced pumping, we explored, in our simulation, various pumping regimes of HPLS to observe its effect on a seeded BR beam of 0.35 J (equivalent to $\approx 0.2\%$ reflected from target at 10 PW). The evolution of BR across the amplification chain for various pumping scenarios chosen is shown in Figure 7.

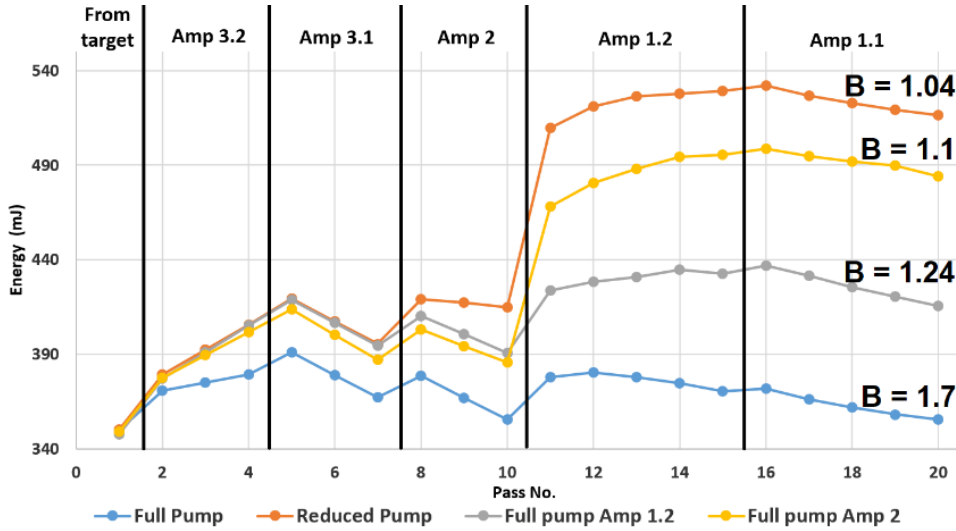


Figure 7 Monitoring BR amplification across HPLS for the presented scenarios. The order of amplifiers is in line with propagation of BR light.

Utilizing the presented tools, we have successfully managed to overlap our amplification simulation of HPLS (i.e. from Dazzler to Amp 3.2) with its real counterpart in both spectral and energy content as seen in following figure.

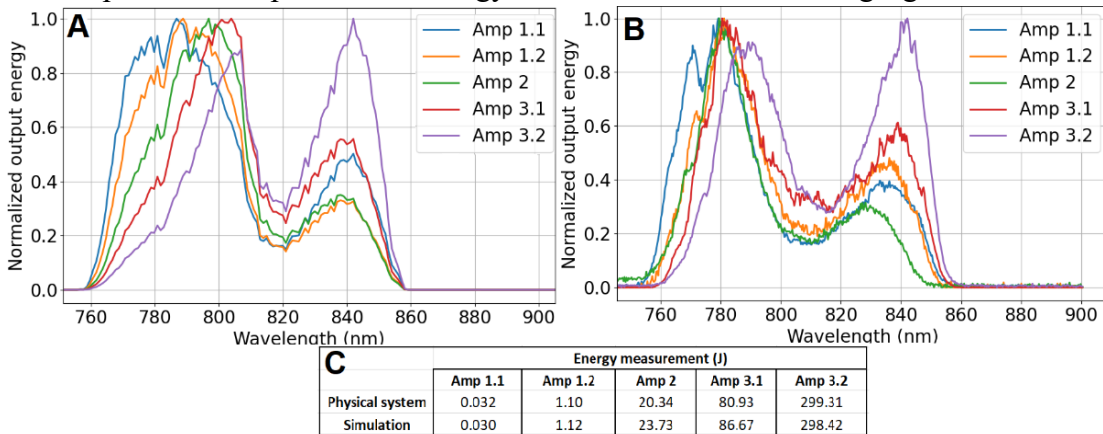


Figure 8 Normalized energy and spectra output of each amplifier in the chain. A - simulated amplification in spectral domain. B - acquired spectra from each amplifier during 10 PW experimental campaign. C - Measured and simulated energy for each amplifier.

Commissioning of back-reflection monitoring system for multi-PW irradiation of solid targets

Here we present two new tools for the 10 PW facility dedicated to measuring the BR light from target, which are adapted to the features of the laser system, beam transport and experimental area. The laser pulses incident on target can have a peak energy ~ 240 J, pulse duration of ~ 24 fs, center wavelength $\omega_L = 810$ nm and p- polarization. The beam is focused on target in a spot with diameter of a few microns by an off-axis parabolic mirror (OAP) with a focal length of 1500 mm and $F\# = 3$.

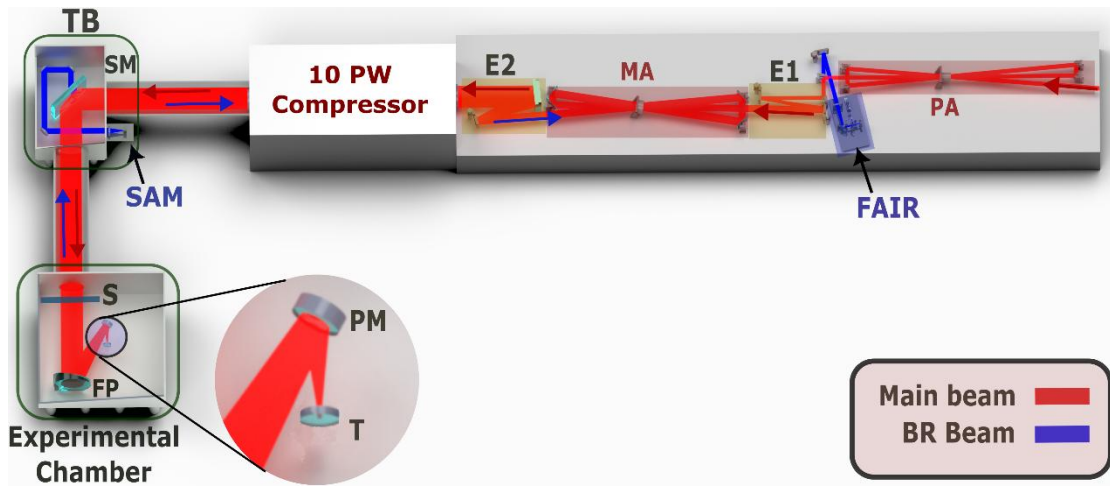


Figure 9 Overview of laser-experimental setup and locations of FAIR and SAM; the labels stand for A3.1-10 PW Preamplifier, A3.2-10 PW Main Amplifier, E4-Forth Optical expander in amplification chain, E5-Fifth optical expander, TB- Turning Box, SM-Steering Mirror,

We describe in the followings the Full Aperture Image Relay (FAIR) system followed by the Small Aperture Monitoring (SAM) system. We present the design and implementation of these two systems, FAIR and SAM, dedicated for the experimental area where laser pulses incident on target reach multipetawatt level. By combining a full-aperture approach in the laser chain and a small-aperture method at mid-distance from the target, we gain insights into temporal, spatial, energetic, and divergence characteristics of the BR light. Through this approach, we address the issue of monitoring the BR in high-power laser-solid target interactions.

Full aperture image relay (FAIR) system

FAIR is designed to capture the full aperture of the BR beam and analyze its features. It was developed with our specialized ray transfer matrix analysis software which served as the basis for both its design and implementation. At its core, FAIR is a Keplerian telescope made of two lenses L_1 and L_2 , with focal lengths $f_1=800$ mm and $f_2=37$ mm, respectively, having an input aperture with diameter 160 mm. Thus, the total magnification $M \approx 0.027$ is used to image an object placed at distance d_o onto a CCD found at a distance d_i , whereas the magnification of only the FAIR telescope is $f_2/f_1 \approx 0.046$:

$$d_o = d_i \left(\frac{1}{M} \right)^2 \quad (19)$$

To be able to observe the evolution of the full aperture BR beam close to the laser system optics, FAIR was installed inside the HPLS, between the 10 PW preamplifier and the main amplifier, where the beam is 100 mm in diameter. BR light is picked-up from the leakage of a dielectric, high-reflectivity mirror with a transmission factor of 0.2%. Between the telescope lenses, through a beam splitter (BS) with the ratio of transmission to reflectance 98% / 2%, a fraction of the beam is sent to a second CCD camera (FF), provided with a sensor with 2448×2048 pixels and $3.45 \mu\text{m}$ pixel size. From the images captured by the FF camera one can infer the deviation angle of the laser beam from the optical axis with an accuracy $\sim 5 \mu\text{rad}$ and its divergence with $\sim 10 \mu\text{rad}$.

During the campaign for the commissioning of the 10 PW experimental area, several BR pulses were generated by the target or a PM and were captured by FAIR. The surface of the large steering mirror (SM) located in the turning box (TB) shown in Figure 9 was chosen as imaging plane. In Figure 10 we show four instances of FAIR utilization during calibration and 10 PW shots. The transversal profile of the beam after the compressor is shown in the first row, in images A, B, C and D. The corresponding images of BR captured by the NF and FF cameras are shown in the second and third rows, respectively. FAIRS proved to be an invaluable diagnostic tool during multiple multi-PW experimental campaigns. It successfully captured a large number of BR images across different target configuration. Despite the diversity of experimental conditions, the images consistently exhibited similar structural features, while the signal intensity varied significantly depending on the type and composition of the target used. Captured images were subsequently post-processed using a custom Python script.

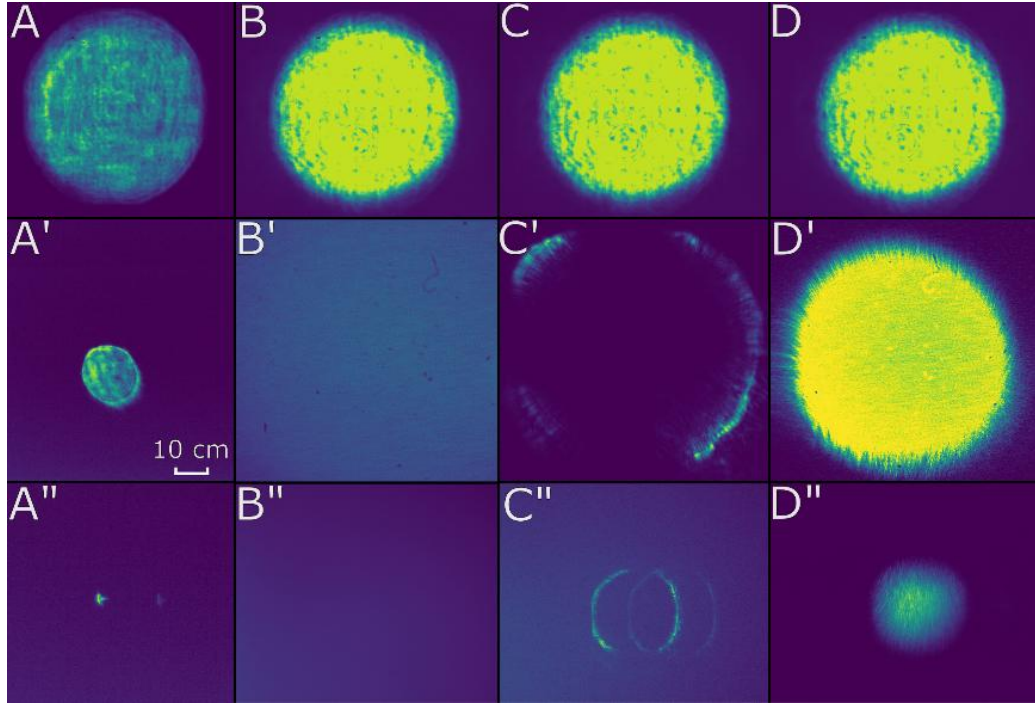


Figure 10 (false-color images) A - Beam profile of the ~ 12 mJ pulse sent to 6" mirror, A' - NF of 6" BR calibration beam, A'' - FF of 6" BR calibration beam. B - Beam profile of the 10 PW pulse sent on a diffusive white screen. B' - Corresponding response of the NF camera with no image; B'' - Corresponding capture by the FF camera with no signal; C - Beam profile of 10 PW pulse sent on target via a PM; C' - Corresponding image of BR beam caught on NF camera during shot on target with PM; C'' - Corresponding image of the shot on target captured on FF camera; the image is doubled by the 2 surface reflection of the BS located in FAIR which splits the beam for NF and FF. D - Beam profile of the 10 PW pulse sent to PM (no target) D' - Corresponding image of BR captured by the NF camera; D'' - Corresponding image of BR caught on by the FF camera.

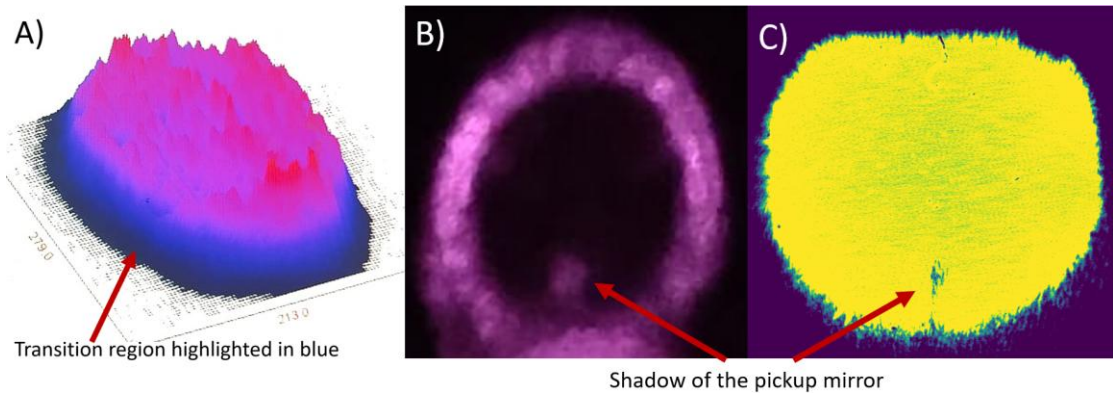


Figure 11 A) 3D map of the intensity distribution across the main beam spatial profile B) Obtained spatial distribution in the PM reflectance test C) NF capture with FAIRS of BR from multi-PW shot

From this reflectance study, we conclude that a used PM introduces significant spatial modulation to an otherwise homogeneous laser beam; a phenomenon illustrated

in Figure 11 B. The observed ring patterns closely resemble the BR traces captured by FAIRS during multi-PW shots. Notably, even small features, such as the "shadow" of the pick-up mirror placed in front of the OAP in the experiment, are clearly reproduced. While it remains uncertain whether the BR beam originating from the target is itself homogeneous, it is now evident that the spatial modulation observed is solely a result of the shot PM's surface features, not due to divergence.

Small aperture monitoring (SAM) system

In the second optical system, we utilize a setup based on a fast photodiode and an optical fiber coupled to an optical spectrometer to detect and record the BR light. Within the TB, three identical dielectric mirrors with diameter 6" optimized for reflection in the range 760-850 nm are positioned in a configuration that collects the central part of the BR beam through the leakage of the large SM. From the positioning of the mirrors, similarly to FAIR, this setup allows for the spatial differentiation between the incoming and BR beams. Data acquisition is done on a 1 GHz oscilloscope with 10 GS/s maximum sampling rate.

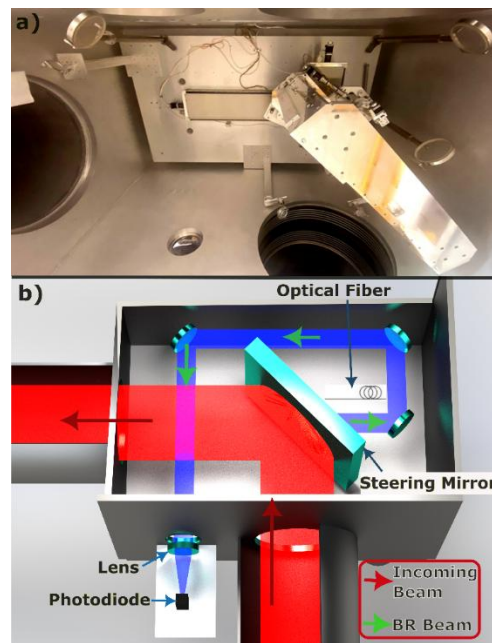


Figure 12 a) Top view of the SAM setup; b) Graphical representation of the turning box (TB) containing the large SM and the optical assembly of SAM. The EMP shielded photodiode is shown in black.

SAM records temporal signals that have a total length ≈ 150 ns, using a fast photodiode produced by Newport Corp., model 818-BB-21 which features a 300 ps rise time¹⁰. It allows the detection of both the trace of the main laser and BR pulses given that the time delay between them is approximately 120 ns. Furthermore, the employed

photodiode was calibrated in terms of incident energy using the main laser which delivered pulses with controlled low energy. This calibration can be extended to a one-to-one equivalence between the BR energy and the measured signal ~ 9.4 mJ to 100 mV peak signal on the scope.

Results

In Figure 13 two shots delivered on screen and target with their respective BR trace captured by SAM are shown. The main laser pulse which is basically direct scattered light from SM together with its artifacts consisting of parasitic scattering inside the TB are visible in both cases, while the BR is seen delayed in time with roughly 98.8 and 114.5 ns from the screen and target, respectively. This correlates well with the distance traveled by light to the screen and target corresponding to 29.64 m and 34.35 m, respectively, and with the physical lengths measured inside the experimental area: 29.75 ± 0.1 m and 35.15 ± 0.1 m, respectively.

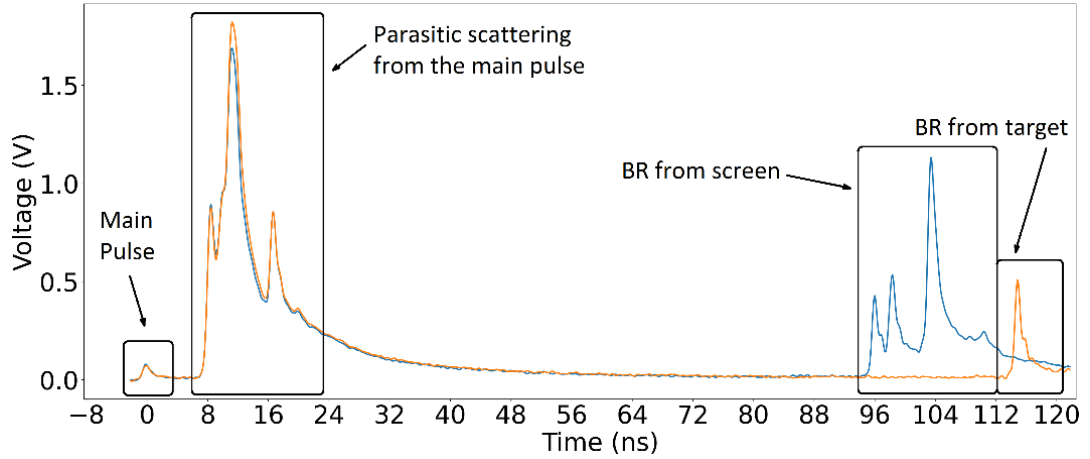


Figure 13 Captured trace of main pulse together with BR light from two separate laser shots: on a white screen and on thin Al foil target with $3 \mu\text{m}$ thickness at 10 PW.

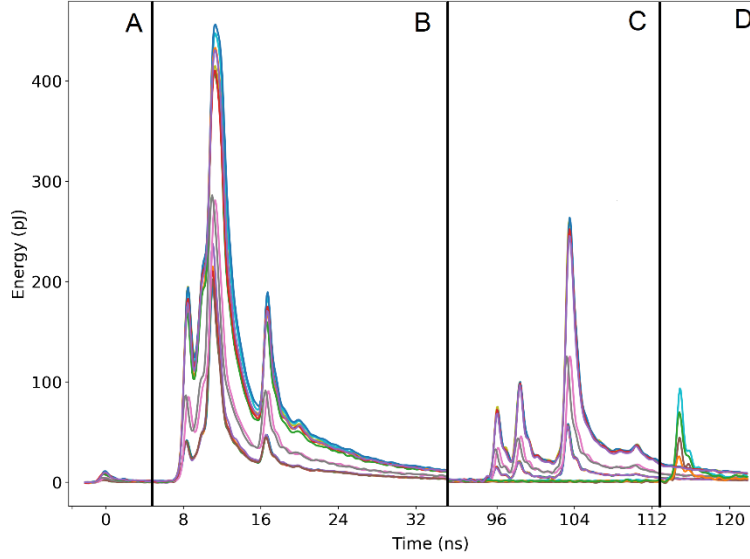


Figure 14 Data from 20 laser shots (with power varying 5-10 PW) delivered to the experimental area on targets and white screen; A) trace of main incident laser pulse, B) Parasitic scattering from the main pulse, C) BR from screen, D) BR from target.

The aforementioned artifacts of the main pulse are produced by the scattering induced while traveling through the vacuum transport system and interacting with optical components such as gratings and mirrors. As such, this strong illumination easily couples into the detector from several directions, which corresponds to the peaks seen in Figure 14 B. The main pulse trace shown in Figure A is barely visible in contrast with the artifacts, as it is highly collimated and aimed towards the target. Initially, it was presumed that the structures observed in Figure 14 A and B represent a strong prepulse followed by the main laser pulse. Later it was confirmed that there is no nanosecond prepulse of this intensity. The optical path of light representing the peak in Figure A is from the SM surface to the viewport and then to the detection system. The first peak in Figure B is scattered light from the SM, collected by the mirror positioned in-line with the viewport. The highest peak comes from the light collected by the mirror placed in the corner of the TB which has a direct view of the back of the SM. Finally, the last peak is from light collected by the mirror positioned close to the back-side of the SM.

The BR trace obtained from the white screen seen in Figure 14 C has a particular temporal structure with 4 peak regions, present in all recorded shots. The PTFE screen acts as a quasi-Lambertian diffuser, thus scattering the light almost uniformly over the entire half-solid angle. We identified that from all the scattered light the 4 clearly defined peaks match with 4 geometrical paths with distinct lengths of the scattered light on its way to the detector. By analyzing the geometry of the vacuum transport system, we determined that the scattered light from the screen that is reaching directly the SM via the shortest path is responsible for the first peak, as it is capable of strongly illuminating the TB. The second peak is delayed to the first peak by the loop of the BR setup shown in Figure 12 which has an optical path of 3.98 ± 0.09 m. The third signal

starts with a sharp increase followed by a slow fall-off that morphs into the fourth peak. This is a large portion of the scattered light from the screen coupling into the vacuum tube which directs it towards the TB and strongly illuminates it.

The experimental data presented in this chapter, obtained through the deployment of custom-built optical diagnostic setups strategically integrated throughout the laser system, offers a valuable complement to the simulation results¹⁸. Not only do the measured back-reflected energy levels align closely with the predictions of our numerical models, but they also serve to mutually reinforce and refine one another – bridging gaps in both theoretical assumptions and empirical observations.

Other contributions to BR mitigation

Reflection-based polarization rotators

As part of the contribution to contrast improvement and BR mitigation I have designed and participated in the execution and installation in the system of several small aperture (compatible with 1" mirrors) and large aperture (compatible with 3" mirrors) double periscopes as well as the installation of the electro-optical switch. The small aperture periscopes which are depicted in Figure 15 B) have been installed with the purpose of beam injection in XPW, OPCPA and optical stretchers. The large aperture periscope seen in Figure 15 A) has been installed to seed the beam into the electro-optical switch. These devices are utilized to replace the present transmission-based wave-plates with reflective-based equivalent without compromising the compatible polarization of injected beam.

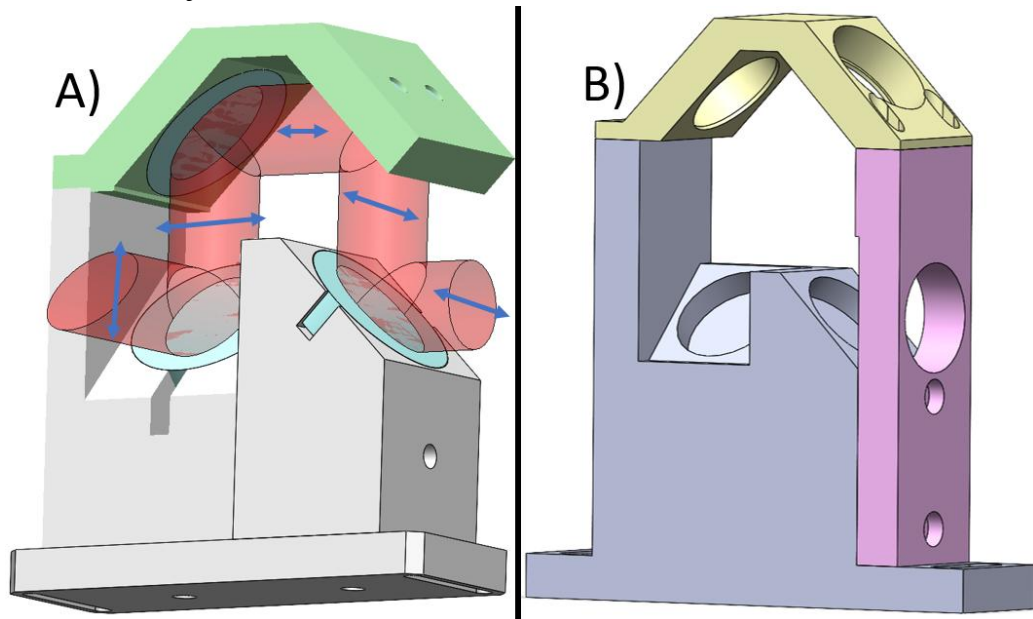


Figure 15 Large aperture (A) and small aperture (B) double periscope design. Note the geometrical mechanism for polarization flip in (A).

To enable successful machining of such a complex piece, the periscope was divided into three parts: the base (which holds the lower two mirrors and can be clamped to any optical breadboard), the roof (which supports the upper two mirrors), and the sidewall (designed to reinforce the structure). While structural reinforcement could have been achieved by simply thickening the mount – making the sidewall unnecessary – the chosen design, with its many thin features, was intended to minimize the mount’s footprint. This was essential for use in areas with high optical component density and also to future-proof the mount for additional applications.

The base includes 7 mm wide slots to allow slight translation and rotation when clamped to the breadboard using two M6 bolts. A similar feature is incorporated into the roof, where four M3 bolts fix it to the assembly. This approach provides much-needed degrees of freedom to accurately position the beam on the mirrors and direct it downstream. The periscope design emphasizes a minimalistic and practical solution – easy to manufacture, align, and maintain – without the need for precision alignment equipment. High-precision alignment is instead achieved via the surrounding kinematic mounts. The metallic periscopes, machined from duralumin (ALU 7075), currently number five and have been performing exceptionally over the past two years.

With the installation of the optical switch, the need arose for an additional polarization rotator, this time accommodating a larger beam diameter of 25 mm. To ensure safe operation and account for the beam’s ellipsoidal profile at 45° incidence on the mirrors, a 3” mirror periscope was designed. However, scaling up to such a large optical mount introduced several challenges. The size of the available raw material limited the maximum dimensions of each component. As a result, the periscope was divided into multiple parts, none exceeding a 100 x 100 mm cross-section. In addition to M6 screws used to secure the assembly, alignment pins were incorporated into the design. These allow for the replacement of degraded optics without losing alignment during disassembly. Despite the presence of thin features in the roof component, the scaled-up form factor significantly improved the overall rigidity of the mount, making the sidewall reinforcement unnecessary in this iteration.

Capturing BR from 1 PW experiments

When the BR beam is generated, it will most likely bear similar divergence to the main beam. Subsequently, it will encounter the burned PM, where it will deposit a significant portion of its energy, and be recollimated and sent into the beam transport back into the HPLS by the OAP. At the optical compressor, it will be stretched (negatively chirped – i.e. “blue” light travels first); note that any light generated due to various phenomena on-target, outside the 700-900 nm spectrum, will be further attenuated by the dielectric mirrors and spatially filtered by the compressor. This passive spectral filtering

simplifies the acquisition process, effectively ensuring that that all captured signals are from the fundamental beam in nature.

After the compressor, the beam enters the HPLS via a periscope which flips its polarization (where it will now travel in air). A photodiode (DET10A2) was installed under the lower periscope mirror on the direction of its leakage for the BR. Prior to installation, the photodiode was calibrated in energy as follows: during the beam delivery at 3.2 mJ alignment configuration to E5, the diode was placed on the leakage direction of the lower periscope mirror of the main beam where a signal of ~ 70 mV was captured. Based on this signal, the calibration of 21.8 mV per mJ was obtained. As per the technical specification of the photodiode, the installation and attenuation of it must ensure signal strength within 100 mV for linear signal response, or at the very least under 1 V for a quasi-linear response; this ensures the validity of the energy calibration across the captured signals. After the installation, the diode was left connected to a Tektronix oscilloscope which can be remotely accessed from control room.

Besides the photodiode, a long-range imaging system was designed and implemented in HPLS, to capture BR light at 10 PW from a leakage of a mirror situated between Amp 3.1 and 3.2. Based on this design, I have developed a compact short-range telescope (later referenced RAT, based on its appearance) with $M = 7.5$ and imaging distance of 100-1000 mm. Its architecture is seen in Figure 16. RAT effectively reduce the 55 mm beam to a manageable 7 mm diameter which can be captured by a CCD. The main focus of the device's design was to achieve a small footprint and maintain a simple architecture. It is based on a Keplerian telescope configuration with focal lengths of $f_1 = 150$ mm and $f_2 = 20$ mm, resulting in a total assembly footprint of $280 \times 70 \times 80$ mm. Due to this compact form factor, the light-tight enclosure and several opto-mechanical components were specifically designed for 3D printing. These parts were fabricated using a nylon filament reinforced with continuous carbon fiber strands, selected for its high thermal resistance and exceptional mechanical properties. This execution strategy was possible with Markforged Mark 2 3D printer; one of the few printers capable of continuous carbon-fiber reinforcement. Among the 3D printed elements, a custom rail system was developed to enable precise positioning of the second lens (for telescope alignment) and the CCD (for imaging distance adjustment). To compensate for the looser tolerances typically associated with additive manufacturing, the carriage system employs an expanding geometry using set screws for fine adjustment. Accurate operation of this dual-axis translation stage is ensured using M6 threaded rods. Internal studies conducted at HPLS identified one key drawback of this composite material: its relatively high sensitivity to moisture and temperature compared to traditional metallic components.

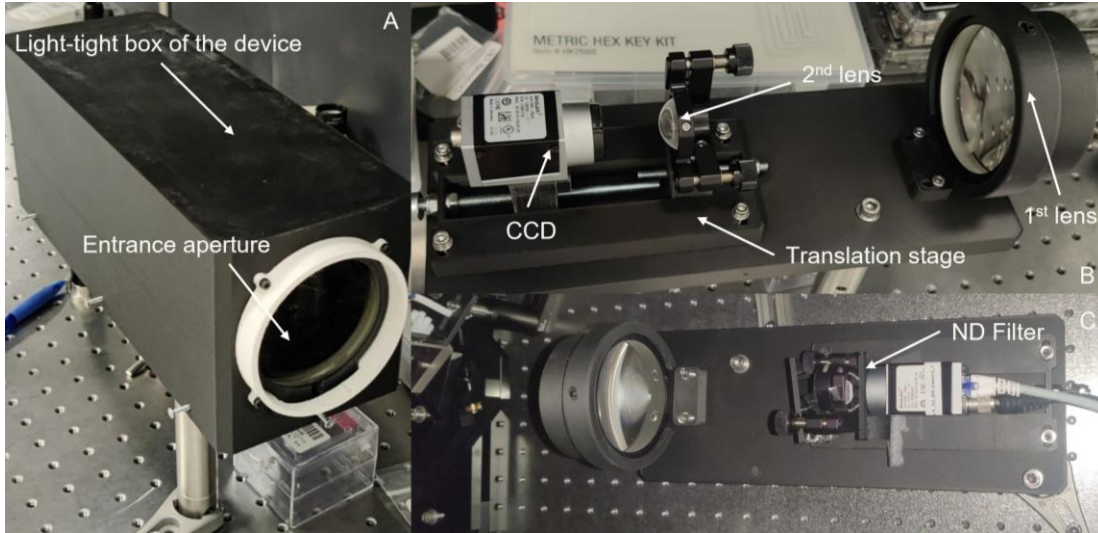


Figure 16 Physical device assembly. A) Assembled device in light-tight box, B) Alignment of the telescope and CCD, C) Installation in HPLS

However, for this particular application, where the primary requirement is simply to capture the relatively large beam onto the CCD, such deviations are imperceptible. It is worth noting that for near-field (NF) and far-field (FF) optical diagnostic devices, this design approach would need to be reevaluated. The current assembly allows for both horizontal and vertical mounting configurations. Overall, the mechanical design and manufacturing strategy employed here proved to be optimal for this application, offering sufficient precision, a robust structure, reduced cost, and a flexible and miniaturized form factor when compared to commercially available specialized solutions.

Rat was installed closely to the photodiode, capturing the leakage of the next steering mirror present in HPLS. To facilitate its alignment, a laser diode at 800 nm with adjustable power output was used in combination with a collimator which enlarged the beam to 40 mm; utilizing the existing alignment references in HPLS, the diode was placed near the periscope and sent upstream. The RAT was aligned utilizing the leakage of a mirror while the imaging plane was set at the said mirror, situated roughly at 400 mm away from the device, by placing hard edge objects such as an iris. This constitutes the rough alignment of the device; further alignment was done utilizing the 1 PW configuration of HPLS at low energy (i.e., 2 mJ per pulse). To simulate BR, a corner-edge retro-reflector was placed in the experimental chamber in front of the OAP. Rat alignment was fine-tuned to center BR beam onto the CCD. Due to a Sapphire window presented in the beam transport system, the spatial profile was distorted. The captured leakage of the BR beam during alignment validates both our alignment and synchronization. During the experimental campaign, dozens of high-power shots were delivered on both screen and target. The available diagnostics have captured the BR traces of these shots. The energymeter placed in the optical switch captured energies ranging between 0.2 – 0.7 mJ with the exception of 2 days across the 1-month experimental campaign where it captured 2.3 – 3.6 mJ. Based on these facts, we conclude that little (if any) BR light has managed to reach this stage of amplification,

and most likely the captured data is prevalently “noise” from the surrounding amplifiers.

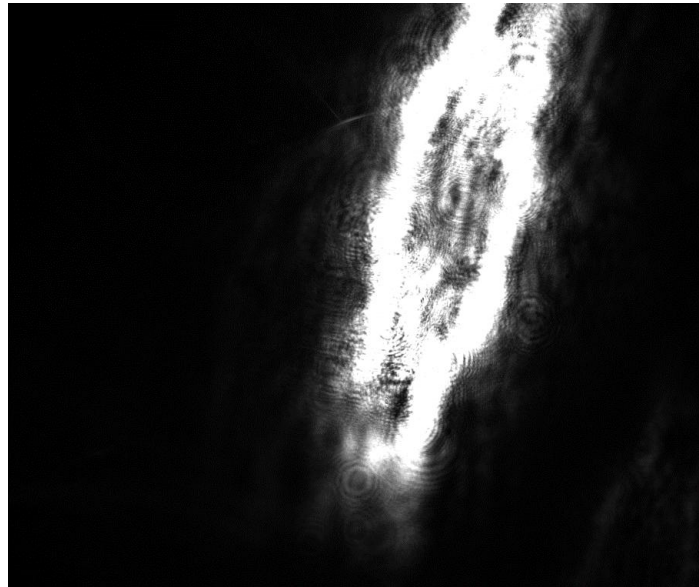


*Figure 17 Image captured with HPLS reflected from E5 utilizing a retro-reflector.
Note the beam is distorted due to 2-passes through the sapphire mirror*

The low BR signal is corroborated by the installed photodiode in the other end of HPLS: during the high-power shots, it was successfully triggered by the scattering of the main beam, and has managed to capture small signals for BR light. The signal is placed at around 430 ns (i.e. 129 m) from the main beam (which is the expected round-trip duration for this configuration as the position of the photodiode from the target is located ~ 65 m), is ~ 13 mJ, and presents little fluctuation from shot to shot. The added value of the photodiode in this low-signal scenario, is that, unlike the energymeter, it discerns between main and BR pulse, offering a certainty for the BR existence. Utilizing RAT, we have successfully captured images during high-power shots. The reduced BR signal observed, compared to previous campaigns, could be attributed to the significant effort made across the last 3 years for the improvement of the temporal contrast on the laser side as well.

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