Transmission final lenses in the HiPER laser fusion power plant: system design for temperature control

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Abstract

The European laser fusion project HiPER is developing technologically feasible components for a laser fusion power plant with an evacuated dry wall chamber which is likely to operate with a shock ignition scheme and direct targets. One of the key components is the final optics. In this work, we consider silica transmission final lenses and address the major issues regarding the unavoidable neutron irradiation they must withstand. For pre-commercial power plants (150 MJ target yield at 10 Hz) a distance of 16 m between the final lenses and target leads to maximum lens temperatures within tolerable limits. However, a non-uniform steady-state temperature profile is a major concern because it is the origin of unacceptable aberrations that severely affect the target spots. We have devised an active intervention system based on a heat-transfer fluid to keep the temperature profile as smooth as possible. The main characteristics of the temperature control system are defined throughout this work and enable the operation of the plant, both for the start-up procedure and for normal operation.

1. Introduction

Currently, the National Ignition Facility (NIF) is devoting its efforts to the demonstration of fusion laser ignition [1]. Recent achievements are very promising for the development of laser fusion. However, technological developments are needed to reach the goal of building a power plant. Several projects are already working on this goal, notably, LIFE [2] in the US and HiPER [3] in Europe. In commercial fusion plants several new aspects will have to be considered, in particular those related to materials under irradiation. One of these problems is studied in this paper: the effect of neutron irradiation on the final lenses of HiPER.

The final optics assembly (FOA) must be protected from the α , β , γ particles, charged particles and neutrons stemming from the target explosions at the chamber centre. In fact, whatever the solution is, at least one optical component will be in the field of view of the radiation and the debris from the target. In order to avoid or minimize back reflected light or any kind of radiation from the target, it is necessary either to focus the beam with optical components far from the target (and so

far a large focal length will be required), or to tighten the beam with a small pinhole (in the radiation shield made of concrete) somewhere close to the chamber wall.

The solution adopted in HiPER is the use of a cassette of lenses with or without debris shields. This design has been detailed in [3] and is shown in figure 1. With this design, a 4 m focal length gives a total distance between the target chamber centre and pinhole of 16 m because the lens is placed at a $2f-2f$ position (magnification = -1). The size of this lens is $0.75 \times 0.75 \text{ m}^2$ and the clear aperture for the beam is $0.6 \times 0.6 \text{ m}^2$.

An alternative to the cassette of lenses is the use of grazing incidence metallic mirrors (GIMM). GIMM have been designed and tested during the high average power laser program [4]. The real drawback of the metallic mirrors (apart of radiation-resistance considerations) is the distance from the target: 24 m to the focal point, which is three times longer than the NIF/LMJ focal length (8 m); so far it is almost impossible to reach the same beam pointing accuracy on the target [5].

The use of the cassette of lenses chosen for HiPER is analysed in this paper. Following previous studies [6, 7] we

Figure 1. A schema showing the configuration of the final lens in the HiPER pre-commercial power plant. The laser is transported in the laser chain and passes through the FOA where it is smoothed and shaped. Then the laser passes through the pinhole that protects against irradiation and is finally focused onto the target by means of the final lens.

analyse problems related to neutron irradiation on the silica transmission final lenses, particularly the dependance of the lens focusing on temperature, both during the start-up and during normal operation. We show that a temperature control system is a must for proper lens performance and discuss several possibilities, concluding that the only realistic solution requires the use of a hot gas flow. Finally, we discuss the different design conditions and parameters used in this work. Although some parameters used in this study may differ from those finally used for the HiPER system, the purpose of this study is to provide a starting point for a realistic conceptual design that can be considered as a reference.

2. Methodology

2.1. HiPER final lenses: design conditions

In order to minimize risks, HiPER will be divided into different phases aimed to prove continuous mode operation in a laser fusion power plant. A pre-commercial power plant will produce an output power close to that of a commercial power plant, ~ 1 GW. For this purpose high gain targets (yield around 150 MJ) should be designed, operating at high repetition rates (~ 10 Hz). For the HiPER project, shock ignition, an advanced direct drive ignition scheme [8], is the preferred option. This scheme will use 48 laser beams to obtain a symmetric target illumination [9]. Each beam is also divided into a bundle of beamlets to produce a zooming effect [10]. The zooming effect is obtained with the arbitrary beam selection (ABS) system. It allows switching on and off the appropriate beamlets at each stage of the ignition scheme. Three types of beamlets are proposed in this work (see figure 2), for the different stages (foot, compression and shock). The beamlets are shaped and smoothed in the FOA, and then relayed through a pinhole of ~ 4 mm diameter (see figure 1). Finally the beamlets are focused onto the deuterium-tritium (DT) target with the use of silica transmission lenses. We assume square biconvex lenses divided in a configuration of 4×4 quadrangles. Each lens quadrangle is used for a laser beamlet with the configuration shown in figure 2. When each laser beamlet is focused onto the target they have a super-Gaussian profile, $I = I_0 \cdot \exp(-(r/\Delta)^m)$, where $m = 2$, $\Delta = 0.62 \cdot R_0$ and

R_0 is 2, 1.25 or 0.5 mm for the foot, compression and shock beamlets, respectively. This choice for R_0 is based on an initial target radius of 2 mm. Targets of around 2 mm are necessary for target gains of 150 MJ. The critical radius during the shock has been taken as ~ 0.5 mm [9] and finally we have considered an intermediate size for the compression stage.

The dimensions of the final lenses are limited by laser damage. Damage in silica with nanosecond lasers appears for fluences higher than 10 J cm^{-2} [11]. For a target yield of ~ 150 MJ, a laser shot of ~ 1 MJ (in 48 beams) is needed. This energy is deposited along the different stages (foot, compression and shock). The compression is the most demanding stage accounting for 75% [12] of the deposited laser energy. The remaining 25% will be mostly deposited during the shock stage. In order to keep the laser energy density below 10 J cm^{-2} , the dimensions of the lens are $60 \times 60 \text{ cm}^2$. With these dimensions, a laser fluence of $\sim 8.7 \text{ J cm}^{-2}$ will be reached during the compression stage and $\sim 5.8 \text{ J cm}^{-2}$ during the shock stage.

Once the lens dimensions are defined, it is important to address the lens distance to the target. The distance is first determined by the irradiation conditions and the maximum working temperature, assumed to be 1223 K [13]. We already pointed out in [6] that the intense ion pulses generated during the explosions of direct drive targets produce local melting with just one shot. Therefore, ion mitigation strategies must be adopted. Assuming full ion mitigation, the lenses are irradiated only by the fusion neutrons and x-rays.

In [6] we studied the lens behaviour for a prototype plant with an output power of 50–500 MW (1–10 Hz, 50 MJ). Under these conditions it is possible to place the lenses at 8 m keeping their temperature below 1223 K. However, in the case of pre-commercial conditions (10 Hz, 150 MJ) the lens should be placed further than 8 m in order to keep the lens temperature below 1223 K. Moreover, as discussed in this work, keeping the temperature below 1223 K is not the only condition necessary for the operation of the lens. In addition, it is necessary to keep a flat temperature profile along the lens and a constant temperature over time (section 3). Even making use of a sophisticated temperature control system based on a flow of gas (discussed in section 4), the most optimistic temperature

Figure 2. The final lens is divided in 4×4 quadrangles for the different laser beamlets. The foot beamlets pass through the four quadrangles of the corners (blue), the compression beamlets through the eight quadrangles of the sides (green) and the final shock beamlets through the four central quadrangles (red). The different laser beamlets are focused onto the DT target forming super-Gaussian profiles of different sizes (right).

profiles at 8 m turn out to be inappropriate (details are given in the appendix).

Assuming a realistic situation, i.e. biconvex transmission silica lenses, pre-commercial power plant conditions and direct drive targets, we must accept that the final lenses must be located far away from the targets. Therefore, in this work, we have set the lens position at 16 m from the targets. It will be shown that at this distance, it is possible to design a temperature control system that assures correct performance during all possible power plant operation regimes (start-up, normal operation and special operation modes). Also, although outside the scope of this paper, it is interesting to note that the larger the distance between the final lens and target, the easier it turns out to be to implement an ion mitigation strategy, which will have to be mandatorily implemented for power plant operation.

Once the lens position is set, a number of important parameters can be calculated, such as the focal length, the lens thickness, the neutron flux and the neutron-generated light species in the lenses. We discussed in [14] the methodology to obtain these parameters and in table 1 there is a list of the design parameters employed in this work.

2.2. Figures of merit

An evaluation of the final lens optical performance is necessary to assess the validity of any possible final lens system. In particular, the effect of aberrations on the illumination uniformity must be addressed. A poor uniformity level will lead to instabilities during the target compression process.

The illumination uniformity level is quantified through its root mean deviation (σ):

$$\sigma = \frac{\left[\int (I(\Omega) - \bar{I})^2 d\Omega \right]^{1/2}}{\sqrt{4\pi} \cdot \bar{I}} \quad (1)$$

where $\bar{I}$ is the average intensity, I the intensity at the target surface and Ω the integration variable.

Table 1. Design conditions for the HiPER final lenses. Irradiation conditions from [14].

Parameter	Value
Number of lasers	48
Ignition scheme	Direct drive–shock ignition
Target gain	150 MJ
Repetition rate	10 Hz
Beam profile	$m = 2$, $\Delta = 0.62 \times R_0$
Target radius R_0	2 mm, 1.25 mm, 0.5 mm, respectively
(foot, compression, shock)	
Lens distance to chamber centre	16 m
Lens focal length	8 m
Lens size	$60 \times 60 \text{ cm}^2$ (4×4 quadrangles of $15 \times 15 \text{ cm}^2$)
Maximum lens thickness	28 mm
Neutron flux in the lens	$2 \times 10^{17} \text{ m}^{-2} \text{ s}^{-1}$
Averaged power density due to neutrons	510 kW m^{-3}
Hydrogen production in the lens	49 appm/fpy
Helium production in the lens	83 appm/fpy

To guarantee that the illumination uniformity is suitable for ignition, σ should be kept below 1% [15]. This requirement applies especially during the foot and compression stages because instabilities are formed in these stages. The illumination uniformity depends on several factors. The most important are geometrical restrictions (beam line configuration), system errors (pointing errors, target positioning) and the beam super-Gaussian profile. The illumination uniformity dependency on these factors was studied for HiPER in [15, 16]. In this paper a new factor is introduced: the dependence of the illumination uniformity on the temperature of the final lens. Although the illumination uniformity (σ) is the most important parameter, we have also studied the efficiency of laser deposition (η). The efficiency is calculated as the ratio of power deposited in the target to the

laser power

$$\eta = \frac{\int I(\Omega) d\Omega}{P_0} \quad (2)$$

where I is the laser intensity, Ω the integration variable in the target surface and P_0 is the laser power.

2.3. Methodology

Once the design conditions of HiPER are known (table 1) and the figures of merit defined, it is necessary to address the final lens performance. A multicode approach has been used for this purpose involving different fields such as neutronics, optics and fluid mechanics.

The neutron irradiation of the final optics has been calculated with MCNPX [17] using nuclear libraries ENDFVII [18]. The neutron source is obtained from the Aries project [19]. With the neutron dose, the temperature profile in the final lens has been calculated using Fluent [20] making use of the fluid properties obtained from the CoolProp database [21]. To retain the detail in the boundary layer, 2D simulations have been performed in different slices of the fluid channel using the $k\epsilon$ turbulence model. For the radiative model, the surface to surface (S2S) model is used.

For the evaluation of the optical performance, a ray-tracing code has been developed with a Monte Carlo approach. The ray-tracing code calculates the focal spot for one laser at each stage of the ignition scheme (foot, compression, shock) for a given lens temperature profile. Finally, the focal spot is projected into the spherical target with the 48 direct drive laser beams of the HiPER project.

3. Temperature requirements

3.1. Temperature limits

Due to neutron irradiation, colour centres are created in the final lenses [14, 22, 23]. As a result, optical absorption at ~ 350 nm becomes appreciable. This is the typical laser wavelength for laser fusion facilities (the third harmonic of solid state lasers that use Nd as a dopant). Therefore, a loss of transparency in this band is undesired. Temperature plays a beneficial role, because colour centres efficiently anneal out at temperatures above 800 K. Continuous operation for long periods of time relies on an efficient mechanism for colour centre annealing, thus the final lens systems must be designed to operate at a temperature higher than 800 K. As mentioned above, the maximum working temperature is 1223 K [13]. Therefore, the final lens operation temperature must be within the range from 800 to 1223 K.

3.2. Temperature variation

In addition, the final lens temperature must be kept constant during all the plant operation scenarios. This is due to the fact that the focal length varies with temperature. For a thin lens the focal length variation with temperature is shown in equation (3)

$$\begin{aligned} \frac{\partial f}{\partial T} &= \frac{\partial f}{\partial n} \cdot \frac{\partial n}{\partial T} + \frac{\partial f}{\partial R} \cdot \frac{\partial R}{\partial T} = -f \left(\frac{\partial n / \partial T}{n-1} + \alpha \right) \\ &\approx -f \cdot \frac{\partial n / \partial T}{n-1} \end{aligned} \quad (3)$$

where f is the focal length, T is the temperature, n is the refractive index and R is the lens curvature radius. The term $\frac{\partial n / \partial T}{n-1}$ is the variation of the focal length related to the variation of the refractive index and α is the material thermal expansion, which gives the variation of the focal length due to geometry variation. For the case of silica $\frac{\partial n / \partial T}{n-1} \sim 3 \times 10^{-5} \text{ K}^{-1}$ [24], and $\alpha \sim 5 \times 10^{-7} \text{ K}^{-1}$ [13], i.e. two orders of magnitude lower⁴.

For lenses located 16 m away from the target, deviations in temperature of ~ 20 K induce variations of ~ 5 mm in the lens focal length. The variation in the lens focal length will divert the laser focal spot. This deviation will be ~ 0.4 mm for the foot beamlets, ~ 0.3 mm for the compression beamlets and ~ 0.1 mm for the shock beamlets. When we compare these deviations with the focal spot sizes, 2 mm, 1.25 mm and 0.5 mm for the foot, compression and shock stages, respectively, we observe that the deviation is significant and affects the energy deposition on the target.

Therefore, the lenses must be designed to operate at their design temperature (T_0). This temperature must be maintained during the different operational regimes (start-up, partial regime or normal operation) and only small deviations are allowed.

3.3. Temperature profile

Biconvex lenses are thicker at their centre (~ 28 mm at 16 m from target) than at the sides (~ 5 mm). This causes a higher energy deposition (from neutrons) at the lens centre than at the sides. Since the thermal conductivity of silica is very low, a steady-state non-uniform temperature profile is established along the radial dimensions of the lens. The result is a significantly higher temperature at the centre than at the sides. Different temperatures in the different parts of the lens (centre, sides and corners) cause optical aberrations.

An example is shown in figure 3 for the compression stage. Beamlets pass through the eight quadrangles of the sides. Figure 3(a) shows an ideal case with all the quadrangles at the same temperature. Each beamlet is focused on a super-Gaussian spot and the superposition of all the laser beamlets illuminates the target with a high uniformity level ($\sigma = 0.16\%$). In figure 3(b) the beamlets pass through the quadrangles at a temperature 20 K higher than the design one ($T_0 = 950$ K). The superposition of the 48 laser beams results in a larger spot and thus, the efficiency (η) is slightly reduced, but the illumination uniformity level is still good ($\sigma = 0.27\%$). Finally, in figure 3(c) the beamlets pass through the quadrangles at different temperatures, half of them 20 K above the design temperature ($T_0 = 950$ K) and the other half 20 K below T_0 . The resulting spot is strongly deformed and not centred. Some regions of the target are overfocused and other underfocused. Due to the lack of symmetry in the temperature profile the uniformity level in the target is not suitable for ignition ($\sigma \gg 1\%$).

Summarizing section 3, the temperature profile along silica transmission final lenses must be as flat as possible, constant during all the operation procedures and within certain limits, 800–1223 K.

⁴ The focal distance is also affected by the lens weight. The deformation due to lens weight is $\epsilon \sim 10^{-7}$. This effect is similar to the thermal deformation ($\alpha \cdot \Delta T$) and its influence on the focal distance is much lower than the variation of the refractive index due to temperature.

Figure 3. An example of the focal spot behaviour under different temperature variations. (Top) a schema of temperatures is shown (green for normal, red for hot and blue for cold). (Middle) the focal spot for one beamlet is shown. (Bottom) target illumination resulting from the superposition of 48 laser beams is shown. Several scenarios are shown. Note that for the laser deposition on the target (bottom) the scales are different.

Figure 4. A temperature control system based on a heating holder and line resistances (red) along the surface of the lens.

4. Temperature control system

In order to fulfil the temperature requirements for the HiPER silica transmission final lenses, a temperature control system must be designed. We have studied the following systems: (a) no control system (i.e. lenses exposed to irradiation) just for comparison, (b) a control system based on heating resistances and (c) a control system based on a heat-transfer fluid.

A description of a system (b) based on heating resistances is given in figure 4. The heating resistances are placed between the lens quadrangles and control the temperature at the quadrangle borders. The centre of the lens quadrangles should remain at an acceptable temperature thanks to heat conduction from the quadrangles borders. However, due to the low conductivity of silica the temperature gradient is high and temperature in the quadrangle centres is not effectively controlled. With a finer grid for the heating resistances the

temperature could be controlled. But a finer grid is not a feasible solution as the laser would impact on the resistances with negative effects, and the complexity of the system would be greatly increased. Therefore, such a solution has been discarded.

In order to have better control of the temperature, a system (c) using a heat-transfer fluid is proposed with much better results. This system is shown in figure 5(c). The fluid will heat the whole lens surface resulting in a flat temperature profile. In the following paragraphs, the conditions to obtain a flat temperature profile as well as other design parameters are discussed.

In the system (c), the fluid is confined in two channels between the lens and silica-made windows. Due to the lens curvature, the channel width changes throughout the channel. Therefore in the flow pattern, the fluid velocity is higher in the middle of the channel than at the inlet/outlet. It is also important to point out that the fluid temperature changes over the channel. The fluid outlet temperature is lower than the inlet temperature. If a parallel flow pattern along both channels is chosen, the temperature profile would not be symmetric, decreasing the uniformity level in the focal spot, similar to the situation depicted in figure 3(c). Therefore, it is necessary to have a counter flow configuration, which leads to a symmetric temperature profile in the lens, optimizing the illumination uniformity. It is also necessary to optimize the channel width. The channel width should be as narrow as possible in order to minimize the fluid flow rate, but wide enough to guarantee an effective heat transfer to the lens.

As operation at temperatures between 800 and 1223 K is required, a gaseous fluid will be used. In order to have good heat transfer conditions, the fluid pressure must be $\sim 100 \text{ kPa}$.

Figure 5. Temperature deviation in relation to the design temperature (T_0): (a) no temperature control system; (b) heating resistances are used between the lens beamlet quadrangles; (c) a heat-transfer fluid is used (CO_2 with a channel of 6 mm in the figure).

A pressure drop of ~ 1 kPa along the channel is enough to set fluid flows able to heat the lens and a fluid temperature of ~ 950 K guarantees that both the lens and windows are above 800 K and the annealing of colour centres is efficient.

The size of the lens and windows is defined by the optical and mechanical requirements. A lens and window size of $60 \times 60 \text{ cm}^2$ is defined in order to keep the laser energy density below 10 J cm^{-2} . The lens thickness at its borders is 5 mm in order to hold the lens. Due to the lens curvature

radius (~ 7.8 m), the lens thickness is ~ 28 mm at its centre. The window thickness must be at least 15 mm to withstand the stresses due to the differential pressure between the fluid (100 kPa) and chamber (vacuum). With this thickness the maximum stress in the window is ~ 40 MPa, below the tensile strength (48 MPa) and the bending stress (67 MPa) [13].

In this work the windows are designed with the minimum thickness that supports the stresses. However if more resistant windows are necessary it is possible to have thicker windows. With thicker windows of 30 mm thickness, the maximum

stresses would be reduced to ~ 10 MPa. Instead of having thicker windows it is also possible to add a support grid that strengthens the windows. The support grid can be introduced between the different lens quadrangles in a 4×4 configuration (similarly to the heating resistances of figure 4). With this solution, the stresses could be reduced to ~ 3 MPa.

The windows do not focus the laser, due to their flatness. There is only a small laser deviation of ~ 0.1 mm along the window. This effect is negligible compared to the size of the lens 60×60 cm². Also, due to the symmetric configuration, this negligible deviation in the first window is corrected in the second window.

The heat-transfer fluid should be transparent to the HiPER laser wavelength (350 nm), chemically stable in order to prevent reaction with silica at the operational temperatures (>800 K) and with good heat-transfer properties. Four fluids that fulfil these requirements have been studied: helium, carbon dioxide, argon and xenon. The use of He allows for thin boundary layers and high heat transfer coefficients. However, since He density is low, high volumetric flows are needed. In the case of CO₂, the channel width should be slightly larger than for helium. However, as CO₂ is heavier, the volumetric flow and pumping power are lower, which can be translated into an easier engineering implementation of the system. Regarding Ar, it presents similarities to CO₂, as both have similar densities. However, Ar thermal conductivity and specific heat capacity are lower, which leads to worse cooling properties. Ar could be an alternative to He or CO₂ in case He permeation or corrosion issues with CO₂ posed any problems in the final implementation of the system. Finally Xe, as the heaviest fluid, presents the worst cooling properties. Xe is of interest if the target chamber is to be filled with xenon gas as in the case of some indirect drive target facilities (e.g. the LIFE project). However, for direct target illumination (e.g. the HiPER project), an evacuated chamber is needed and Xe fluid does not present any advantage for a temperature control system. Neutron interaction with the fluid will be much lower than with silica. Due to the lower fluid density and lower thickness of the fluid channel most of the activation will take place in the silica lens and windows. However, the fluid system will have to be controlled to avoid high activation levels or leakages. The transmutation rate for the fluid will be ~ 100 appm/fpy.

Silica is quite resistant to corrosion by elements or compounds. Exceptions are some acids, alkalis, alkaline-earths and some oxides at high temperature [13]. Therefore, corrosion by the selected fluids will not be a problem, provided the impurity levels are kept under control. Helium solubility and permeation through silica deserve some attention. Helium solubility at ~ 900 K is ~ 5 appm [25] and the permeation flow through the windows at this temperature is $\sim 10^{13}$ cm⁻² s⁻¹ [25]. This gives a total of $\sim 2 \times 10^{18}$ atoms s⁻¹ into the vacuum chamber. This rate is low and can be pumped out by the chamber vacuum system.

Several aspects of system (c), using a heat-transfer fluid, were studied above, and no major problem is expected. In figure 5, a comparison between the different systems (a), (b) and (c) is shown and it is observed that a flat temperature profile can only be obtained with system (c).

For system (a), with no temperature control, we observe in figure 5(a) how the neutron irradiation induces a

steady temperature profile along the biconvex lenses. The temperature profile has a temperature gradient of ~ 100 K, which will induce unacceptable aberrations for plant operation. In addition, it will not be possible to maintain a constant temperature during the different regimes of operation making it impossible to pass from start-up to full regime operation. For system (b), with heating resistances, we observe in figure 5(b) that due to the low conductivity of silica only a small part of the lens is kept at the desired temperature (T_0). The temperature difference between the coldest part (corners) and the hottest one (lens centre) is ~ 100 K. Therefore, in order to guarantee a uniform temperature profile, the temperature has to be controlled over the whole lens surface as proposed in system (c). In figure 5(c) we observe how it is possible to have a temperature deviation of only ~ 20 K when a heat-transfer fluid is used⁵. In the next section, we study how this temperature profile guarantees a focal spot with high illumination uniformity.

5. Optical performance of the temperature control system

The focal spot is highly dependent on the temperature profile and a detailed evaluation with realistic temperature profiles is necessary. The proposed fluids (He, CO₂, Ar and Xe) were analysed to optimize the channel width in order to improve the figures of merit described in section 2.

Figure 6 shows the uniformity level (σ) as a function of channel width for different fluids, while figure 7 shows the efficiency of laser deposition (η) during normal operation. In all the cases, the lens design temperature (T_0) is set at the corner temperature (~ 900 – 950 K). This way, a good illumination uniformity is expected for the foot beamlets, regardless of the fluid or channel width. However, for compression and shock beamlets, the temperature profile may induce aberrations that may lead to poor illumination uniformity.

The shock beamlets pass through the lens centre and the compression beamlets pass through the lens side quadrangles. These quadrangles are at a higher temperature than the corners (foot) due to neutron irradiation and therefore aberrations are introduced. In figures 6 and 7 it is observed how He and CO₂ systems with channel widths higher than ~ 4 – 6 mm have high illumination uniformity ($\sigma < 1\%$) and high efficiency ($\eta \sim 90\%$). For Ar or Xe, due to their inferior cooling properties, the aberrations are higher than for He or CO₂. This causes a higher level of non-uniformities (σ) with lower efficiency (η).

From the analysis of the illumination uniformity and efficiency, we conclude that either He or CO₂ could be chosen. However, it is also important to consider that pumping CO₂ is easier than pumping He, due to its higher density. For a channel of 6 mm, ~ 2.3 m³ s⁻¹ of He should be pumped out, very high compared to only ~ 1 m³ s⁻¹ of CO₂. This, in terms of pumping power, translates to ~ 2.3 kW for He and ~ 1 kW for CO₂. In addition, pumping and handling are easier in the case of CO₂.

⁵ Only the temperature variation in the lens is considered. Regarding the temperature in the window, its effect on laser focusing is neglected due to the window flatness. Also the temperature variation in the window is low, only ~ 5 K.

Figure 6. The uniformity level (σ) for different heat-transfer fluids as a function of channel widths during normal operation for the different ignition stages (foot, compression and shock).

Figure 7. Laser energy deposition efficiency for different heat-transfer fluids and channel widths during normal operation for the different laser beams.

In the previous paragraphs, the illumination uniformity and efficiency at normal operation were analysed. But, what happens during start-up, when there is no neutron irradiation? In normal operation conditions, the lens temperature is defined by the neutron irradiation (510 kW m^{-3}) and the heat-transfer fluid (inlet temperature 950 K , pressure drop 1 kPa). The temperature of the lens is near the design temperature (T_0) and operation of the lens is possible. However, during the start-

up there is no neutron irradiation. If the heat-transfer fluid remains at the same conditions as for normal operation, the lens would cool down and would not focus the laser correctly.

Therefore, it is necessary that the fluid transmits more heat to the lens during the start-up until the lens is at its design temperature (T_0). For this purpose the temperature of the fluid is increased. In table 2 we show how by increasing the fluid temperature during the start-up it is possible to maintain a

Table 2. The main parameters of the final lenses for start-up and normal operation with a channel width of 6 mm.

Fluid	Design T_0 (K)	Operation regime	Fluid T_f (K)	η			σ		
				Foot	Comp.	Shock	Foot	Comp.	Shock
He	947	Start-up	985	92%	92%	92%	0.17%	0.18%	0.46%
		Normal	950	92%	92%	89%	0.16%	0.23%	0.46%
CO ₂	943	Start-up	995	92%	92%	92%	0.19%	0.18%	0.18%
		Normal	950	92%	92%	87%	0.17%	0.28%	0.29%
Ar	926	Start-up	1030	91%	92%	92%	0.21%	0.26%	0.41%
		Normal	950	92%	91%	82%	0.19%	0.25%	0.76%
Xe	909	Start-up	1060	91%	91%	92%	0.35%	0.59%	0.53%
		Normal	950	92%	90%	74%	0.17%	0.37%	1.08%

good illumination uniformity ($\sigma < 1\%$) with high efficiencies ($\eta \sim 90\%$).

In table 2, the design temperature (T_0) of the lens is also presented. The design temperature is set to the value of the lens corner temperature at normal operation when the fluid temperature is fixed. The different heat transfer properties of the analysed fluids, He and CO₂, allow for a design temperature in the range 940–950 K, while the design temperatures for Ar and Xe are ~ 930 K and ~ 910 K, respectively. Therefore, a higher difference between T_0 and fluid temperature is required in Ar and Xe designs.

The same effect is observed for the fluid temperature during the start-up. In order to keep the lens temperature around (T_0), the fluid temperature is raised from 950 to ~ 990 K for He and CO₂, and from 950 to ~ 1060 K for Ar and Xe.

Finally, between start-up and normal operation there will be a transient operation that makes it necessary to adapt the fluid temperature to the neutron irradiation level. Thus, the fluid temperature would be between those corresponding to start-up and normal operation temperatures.

6. Conclusions

Throughout this work we have evaluated the neutron irradiation on the HiPER silica transmission final lenses and how the temperature profile affects the laser focusing. We have shown that laser focusing is quite sensitive to temperature variations and thus the temperature has to be carefully controlled during plant operation.

It is important to maintain a high temperature during operation (>800 K) to promote an efficient annealing of colour centres but below the maximum working temperature of silica (<1223 K). In order to avoid variations in the focal length the temperature must remain constant during operation and uniform along the lens in order to minimize optical aberrations.

A pre-commercial scenario for the HiPER project has been studied. In this scenario final lenses must be placed at a distance of ~ 16 m. In order to control the temperature a heat-transfer fluid system is proposed. Several fluids have been studied. He and CO₂ are adequate to control the lens temperature. CO₂ appears to be the best solution due to its cooling properties and easier engineering implementation. The behaviour of the system at normal operation and during start-up has been studied and it is concluded that it is possible to maintain a good illumination uniformity ($\sigma < 1\%$) and a high efficiency ($\eta \sim 90\%$) by adjusting the fluid temperature.

The main limitations of the proposed solution are the requirement to operate at high temperatures (>800 K) and the necessity to place the lenses at 16 m from the target, which results in large facility dimensions. Other solutions may solve the previous limitations at the expense of adding other potential problems. A careful analysis similar to this work must be performed in order to study alternatives to transmission lenses, e.g. Fresnel lenses or GIMM [25].

With the use of Fresnel lenses the size of the facility could be reduced. Fresnel lenses are thinner than transmission lenses and they could be placed nearer the target (8 m, 12 m). However operation at high temperatures is still necessary in order to anneal out colour centres. The focal length variation with temperature is similar for Fresnel and transmission lenses. Therefore, the temperature control system proposed in this work could be also used with Fresnel lenses as the final optical component. Fresnel lenses offer a good alternative to transmission lenses and are in effect the main option for the LIFE project [26]. The main problem of Fresnel lenses stems from the mechanization requirements, which may lead to laser damage and reduced laser focusing capabilities.

To avoid operation at high temperatures, materials different from silica must be used. GIMM could be a solution but its reflectance is highly dependent on the surface quality, which is altered after neutron irradiation. In addition, laser damage is a concern in metal mirrors, as well as, neutron irradiation-induced creep. Further progress in alloys, probably based on the inclusion of nanometer-sized particles, could improve the radiation resistance of the mirrors. Also, with GIMM, large focal lengths (~ 24 m) are necessary. Therefore, using GIMM the facility size would be similar or even larger than using biconvex lenses.

Finally, it is important to point out that the presented solution is based on the experimental evidence [22, 23] that defects in silica anneal out at high temperatures (>800 K). However, an unexpected response to irradiation could occur since these results are obtained with neutron fluxes far lower than those expected in HiPER and with different neutron spectra. In addition, the effect of gases (hydrogen, helium) or impurities also requires further research under realistic irradiation conditions, because they may induce laser absorption, or even trigger laser damage. Also the impact of stresses induced by neutron interaction, beam polarization and on wave-front distortion should be studied with an experimental basis. Finally, it must be assessed that the combination of effects will not induce mechanical failure in the system due to creeping, ratcheting or fatigue.

Figure 8. Temperature deviation in relation to the design temperature (T_0). A heat-transfer fluid is used (He with a channel of 20 mm). The lens is located at 8 m (a), 12 m (b) and 16 m (c) for the chamber centre.

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Appendix. Analysis of lenses located nearer the target (8–12 m)

Throughout this work we have studied the possibility of controlling the temperature of a lens placed at 16 m from the target. At this distance the pinhole would be placed at 32 m from the target (see figure 1). A more compact solution would be advantageous.

Table 3. The optical performance of the lens at different distances for a case using helium and a channel of 20 mm.

Fluid	Design T_0 (K)	Distance (m)	Fluid T_f (K)	η			σ		
				Foot	Comp.	Shock	Foot	Comp.	Shock
He	918	8	800	78%	37%	5%	2.39%	2.32%	1.45%
	926	12	900	92%	89%	63%	0.17%	0.58%	1.83%
	950	16	950	93%	92%	89%	0.16%	0.46%	0.21%

In order to have a conservative solution, we have studied the system using helium with a channel width of 20 mm. As observed in figure 6, He has the best heat transfer properties (along with CO₂). In addition, increasing the channel width (beyond ~ 10 mm) shows no further improvement.

In figure 8, the variation of temperature in relation to T_0 is shown. It is clearly observed that at 8 m, the temperature variation along the lens is higher than 100 K. Placing the lens at 12 m, the temperature variation is corrected to ~ 40 K and placing the lens at 16 m, the temperature variation is less than 15 K. This reduction in the temperature gradient is caused by the lower irradiation and flatter geometry of the lens located further away from the target.

In table 3, the performance of the lens is shown and it is observed that with the lenses at 16 m the efficiency is high ($\eta \sim 90\%$) and the illumination uniformity is good ($\sigma < 1\%$). However if the lens is placed at 8 m the illumination uniformity is not acceptable ($\sigma > 1\%$). When placing the lens at 12 m an intermediate scenario is found, where the illumination uniformity is good ($\sigma < 1\%$) for the foot and compression beams and worse for the shock beams ($\sigma > 1\%$).

In this work it is concluded that it is possible to place the lenses at 16 m from the target with the temperature control systems proposed. At the expense of increasing the non-uniformities at the end of the ignition (shock beams), it would be possible to place the lenses at ~ 12 m from the target. Finally the lenses cannot be placed much nearer (~ 8 m) as the non-uniformities would increase for all the ignition stages.

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