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HiPER Laser Architecture Principles

B. J. Le Garrec¹, C. Hernandez-Gomez², T. Winstone² and J. Collier²

¹CEA-CESTA, 15 avenue des Sablières, BP2, 33114 LE BARP, FRANCE ²Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom

E-mail: bruno.le-garrec@cea.fr

Abstract. The HiPER project [1] is in a preliminary phase and a risk assessment is being conducted for a generic HiPER beamline concept – this is based on an anticipated requirement for a single beamline (or focal spot unit) drawn from the best available knowledge we have to date of the fusion physics requirement. For the moment the general architecture is to first order independent of the specific beamline implementation (i.e compression phase or ignition phase) as the fundamental requirements are very similar. In this paper we are describing the laser beamline as a bundle of unit beams (or beamlets) and we are explaining that optical zooming is quite possible especially in the case of shock ignition.

1. Introduction

The HiPER project [1] intends to demonstrate fast ignition of laser-driven targets by means of a multibeam, multi-ns laser pulse of about 250-300 kJ for implosion and a short pulse of about 100 kJ delivered in 15 ps for ignition [2]. In this type of direct-drive inertial confinement fusion, the "ignitor" shock can also be launched by a 60 kJ power spike at the end of the laser pulse [3]. At this stage, even proton driven ignition must be considered [4].

On the "laser" side, our objective is to identify the least expensive and most useful driver but not to preclude any alternative laser design that can make the facility more flexible and help achieving fusion.

2. Baseline concepts

The Laser Baseline stems from several key factors that are related to the facility requirements.

2.1. Facility requirements

The conventional direct-drive scheme involves both compression and ignition beams. There is a baseline target [5, 6] but there is of course still great uncertainty as to what this baseline will be.

Compression beams are to be focused as 48 focal spots onto the capsule: 250 to 300 kJ and 50 to 75 TW in a 10 ns shaped pulse at 3 ω . Ignition beams will be either shock ignition beams or fast ignition beams. Shock ignition requires a final 400 ps long spike at 3 ω : 60 to 80 kJ and 150 to 200 TW. High symmetry is not required but smaller focal spots will enhance the laser absorption. Fast ignition will require 100 kJ of 15ps short pulses certainly at 2 ω and the only scheme is the gold conically guided capsule [7]. At this stage, it is not clear whether the ignition beams should be coherently phased or not,

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and a small angle set of 20 to 30 beams overlapping somewhere at the cone entrance is quite tricky to design.

The primary HiPER facility will be operated on a "high" repetition rate basis (typically 10 Hz). Again, this repetition rate is not known precisely because repetition rate, laser efficiency and target gain are related to the cost of electricity that one would expect from the power plant design [8, 9].

This "high" repetition rate basis essentially means (in technological terms) that substantial new laser technology development will be required. This stems from the simple fact that the existing "single shot" technology as used by the National Ignition Facility or the Laser MégaJoule is, in general, not viable for high repetition rate requirements, although certain component technologies or techniques could readily be adapted.

Current "high repetition rate" laser technology based on flashlamps could not be scaled in any feasible or credible manner to the levels of efficiency required by HiPER. Our working assumption is that this beamline will be based on Diode Pumped Solid State Laser (DPSSL) technology [10]. This diode pumped technology is very promising technologically but relatively immature in its development and certainly prohibitive in its cost at today's prices when considering the requirements of the HiPER facility.

The availability, operation and performance of large scale/aperture components and component technologies at high average power are an unknown but essential entity. The level of industrial technological maturity with respect to the laser technology needs of HiPER is still someway off, even if in specific areas the industrial potential is evident.

2.2. Stacking of laser cells and bundle design.

Because roughly 380 kJ is to be focused on the capsule in 48 focal spots and assuming 50 % frequency conversion efficiency, this means that 16 kJ is required at the fundamental wavelength per focal spot.

Our assumption is that one laser beam is a bundle of beam lines (or beamlets) and one bundle is focused as a single focal spot onto the target. This assumption is also based on the fact that the unit cell will have a moderate size: the size is related to the affordability of the optical components that can withstand high average power (diode pumped amplifiers, frequency conversion crystals etc...). There is a trade-off between laser gain, amplified spontaneous emission and non linear effects (SRS, SBS). Let us call "beamlet" one full "unit cell" beam line.

The last generation of fusion lasers has shown that high fluence and low gain were compatible and would not preclude high extracted energy. Nevertheless, high saturation fluence should be considered carefully because the maximum fluence at the amplifier output must be lower than the laser damage fluence of the weakest optical component of the laser. As an example, let us consider $10J/cm^2$ damage fluence and a beam whose near field modulation depth equals 1.5; this means that the average fluence in the beam shall not exceed 6.7 J/cm² and that 1kJ energy can be extracted for a 150 cm² aperture.

At that point, there is one reason why the size of the beam cannot be increased. In fact, the amplified spontaneous emission (ASE) gain in the transverse direction of the beam scales as the diameter of the beam (most of the time, one must consider the diameter or the diagonal size of the component). In a typical 1 cm long amplifier whose transverse size is 10 cm (diagonal size D is approximately 15 cm), the ratio of the ASE gain to the laser gain is $e^{15} \approx 3.10^6$. In other words, small signal gain (g) is limited by ASE as soon as the Fresnel loss at the edges (R) cannot compensate for the transverse gain:

$$g \le \frac{-\ln(R)}{D} \tag{1}$$

When the refraction index is in the range 1.8 to 1.9 (typical values for garnets and sesquioxides), gain cannot exceed 0.12 cm^{-1} . This value is comparable to typical values commonly available in the disk geometry [11, 12]. It is clear that there is a trade-off between gain (limited by ASE effects) and clear aperture of the beam (diameter or diagonal size).

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According to the above values, one beam line could be made of 16 beamlets, each of whom would be able to amplify the fundamental wavelength from the front-end level (tens of millijoules) up to the kilojoule's level. The addition of different pulse shapes is possible while stacking the laser cells as described above. This bundle principle has been successfully tested both on the NIF [13] and the LIL facility [14] with the quadruplet design.

Let us consider that each beamlet has its own phase plate and that the bundle is focused with a single lens (as shown on top of figure 1). This technique is called beam conditioning because a speckle pattern is created inside the focal spot and the focal spot energy distribution can be adjusted with different phase plates: different sizes and different shapes are possible.

In the case of a bundle of beam lines, all the beamlet focal spots will overlap and the speckle patterns from each individual beamlet will mix so that the contrast will decrease, leading to a "smoothed" profile of the focal spot (as shown at the bottom of figure 1).

2.3. Optical zooming

Zooming has been proposed by the Naval Research Laboratory for KrF laser fusion [15] and is widely used in their target designs [16, 17]. Optical zooming means reducing the focal spot continuously or step by step during the pulse. This can be done when every single beam line is associated with an arbitrary waveform generator and a phase plate, leading to a time dependant focal spot as shown figure 2. Our bundle principle allows building different complex pulse shapes and overlapping different focal spots. It is based on time-delayed pulse shapes associated with different beamlets and can be considered as optical zooming [18]. Different phase plates and/or different focal lengths can be used.



Our bundle principle is very convenient in the case of the direct-drive scheme involving both compression beams and shock ignition beams and this has been pointed out recently [19].

Of course and depending on the system requirements, both coherent and incoherent additions have to be made to ensure enabling pulse synchronization, smoothing and coherent propagation of compression and ignition beams down to the target.

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3. Conclusion

We have presented the HiPER laser baseline that is to first order independent of the specific beamline implementation (i.e compression phase or ignition phase). The laser architecture is based on the target symmetry requirement leading to 48 focal spots and roughly 8 kJ at the third harmonic per focal spot.

Assuming Diode Pumped Solid State Laser (DPSSL) technology for the amplifiers, each of the beamline is made of a bundle of unit laser beams (that we call beamlets). Because there is a trade-off between gain (limited by ASE effects) and clear aperture of the beam (diameter or diagonal size), it seems reasonable not to exceed the kilojoule energy level per beamlet. So far, one bundle will be made of approximately 16 beamlets. The good thing is that this bundle principle allows performing optical zooming as soon as it is possible to associate one arbitrary waveform generator and one phase plate per beamlet.

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