New amplifying laser concept for Inertial Fusion Driver

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Abstract. This paper presents a new amplifying laser concept designed to produce high energy in either short or long pulses using coherent or incoherent addition of few millions fibers. These are called respectively CAN for Coherent Amplification Network and FAN for Fiber Amplification Network. The fibers would be large core or Large Mode Area (LMA) which have demonstrated up to 10 mJ output energy per fiber\textsuperscript{1}. Such a system could meet the driver criteria of Inertial Fusion Energy (IFE) power plants based on Inertial Confinement Fusion (ICF), in particular high efficiency and high repetition rate.

1. Introduction

One critical issue for the realization of Inertial Fusion Energy (IFE) power plants is the driver efficiency. Over the years, a large effort has been undertaken by the laser fusion community to develop efficient pumping sources like diodes, efficient amplifying media with superior conductivity, like ceramics \cite{2, 3} and new architectures \cite{4} for improved pumping and heat management. Systems based on guided wave such as diode-pumped Yb: glass fiber -amplifiers with a demonstrated overall efficiency close to 70\% look very promising. Guided optics provides the enormous advantage to directly benefit from the telecommunication industry where components are made cheap, rugged, well tested, environmentally stable, with lifetimes measured in tens of years and compatible with massive manufacturing. In this paper, we are studying the possibility to design a laser driver solely based on guided wave optics. It represents a profound departure from already proposed laser drivers all based on free propagation optics. To minimize the driving laser energy, we will adopt the direct drive and fast ignition concept.

2. Conceptual design of a laser driver for inertial fusion

2.1 Fiber lasers

The system will use a large number of identical Large Mode Area (LMA) fibers (~10\textsuperscript{7}) to combines long (ns) and short (ps) pulses. The fibers will be diode pumped, leading to a highly reconfigurable ensemble with very high efficiency and good beam quality.

The best fiber for our application is the Yb:glass fiber. It offers the following advantages:
- simple energy levels, no excited state absorption
- broad emission bandwidth (~40 nm)
- broad absorption band overlaps with diode wavelengths
- small quantum defect leading to optical-to-optical efficiency >80%
- large saturation fluence $F_{\text{sat}} = 50 \text{ J/cm}^2$
- long fluorescence lifetime ~1ms

A large energy level will require a large core or Large Mode Area (LMA) while maintaining single mode behavior. This is a serious difficulty that can be circumvented by:

a) bending the fiber resulting in more losses for the higher-order modes. Also, larger dimensions ~100$\mu$m can be obtained by using holey core. The transfer between pump and signal can be achieved efficiently by using double-core fibers where the pump is injected in a large core (highly multimode) and the signal in the smaller core (single mode). The transfer between the two fibers is due to the higher pump modes crossing and therefore pumping the single mode core. The transfer between pump to signal can be 90% efficient leading to an efficiency between the pump laser and the signal of 80% [5]. If we consider that the diodes themselves can be 80% efficient, the wall-plug-to-laser output efficiency could therefore be as high as 60%.

b) extracting efficiently the stored energy from a LMA multimode fiber, in a single mode beam via nonlinear processes such as Stimulated Brillouin Scattering (SBS) or Stimulated Raman Scattering (SRS) as shown by [6].

2.2 Amplification network architecture

For the fast ignition scheme the laser system will integrate two types of pulses: long (ns), shaped compression pulses, and short (ps), ultra intense igniting pulses. The actual point design of HiPER, the High Power laser Energy Research facility project in Europe, is based on 200 kJ of long pulse and 70 kJ of short pulse. Assuming 10 mJ per fiber, the driver must have around $3 \times 10^7$ fibers. A seed pulse, is amplified by a Large Mode Area (LMA) Yb: glass single mode amplifiers up to an energy level corresponding to the saturation fluence $F_{\text{sat}}$. It is then divided equally into many branches where each individual pulse is amplified again to the same level as previously.

For the compression pulse, no coherent addition is demanded. The required ~1 : $10^7$ total splitting ratio is achievable with a total of four splitting stages: first stages with 1 : 128 times, second and third stage with 1 : 64 times and finally the fourth, with 1 : 128 splitting. The inevitable loss of each splitting stage must be balanced by a gain in fiber amplifiers inserted between the splitting stages. Overall gain balance is selected such that ns long -pulse energy in a single-mode fiber never exceeds ~10-mJ, so that optical damage can be avoided and nonlinear effects in each fiber amplifier stage are kept under control. Note that the number of optical paths (optical branches) increases correspondingly after each splitting stage, so that there are 128 branches in stage II, 8192 branches in stage III, and 524288 branches in stages IV and greater than 10^3 in stage V. It is important to emphasize that all branches in each particular stage are made from exactly identical components. This should significantly simplify parts procurement for this complex system.

One data sheet example of commercial 1:32 and 1:4 fiber-star splitters can be found at [www.fira.com](http://www.fira.com). This particular device can ensure 1:32 splitting ratio with 17-dB to 18-dB insertion loss (32-times splitting is 15-dB loss per each channel + only 3-dB extra device loss) and 1:4 splitting ratio with ~7-dB insertion loss. 1:2 splitters are very standard with typical insertion losses of ~3.5-dB. Required splitting ratios of 128-times and 64-times can be either achieved by multiplexing the above splitters ($128 = 32 \times 4$ and $64 = 32 \times 2$), or fabricating single-stage star-couplers with required splitting ratios. Consequently, we can take as an estimate of the insertion loss per splitting stage to be ~25-dB per 1:128 stage and ~22-dB for 1 : 64 stage. Detailed distribution of gain in each fiber amplifier stage of each optical branch is shown in Table1.

An important technical aspect to be considered here is the use of active optical gates between different amplification stages. The purpose of these gates is twofold. First, optical gate at the input of stage I is used to down-count pulse repetition rate from initial 50-100-MHz from a mode-locked seed to ~50-Hz in the fiber amplifier chain (necessary for high-energy pulse extraction). Second, additional gates are required at the duty end of each fiber amplifier stages I, II and III (and prior to each
subsequent fiber-star splitter) in order to suppress Amplified Spontaneous Emission (ASE) between the amplifier stages, i.e. to ensure that average power in amplified pulses exceeds that of the ASE background of each of the fiber amplifier stages. Based on common practice the best devices for this are fiber-pigtailed Acousto-Optic Modulators (AOM), since they can achieve on-off extinction ratios higher than 80-dB.

| Stage I | Stage II | Stage III | Stage IV | Stage V |
|---------|----------|-----------|----------|---------|
| Splitter | 1 : 128  | 1 : 64    | 1 : 64   | 1 : 32  |
| Number of branches | 1 | 128 | 8192 | 524288 | 16X10^6 |
| Gain | +~20dB | +~30dB | +~22dB | +~22dB | +~22dB |
| Output energy | 10mJ | ~1.3 J | 82 J | 5.3 kJ | 160 kJ |

*Table 1 : Scheme of the Fiber Amplification Network (FAN).*

The fast ignition pulse will be based on Chirped Pulse Amplification. Because the compressed beam duration is around 10ps, we could start with a long (10ns) stretched pulse which is much more favourable from the standpoint of energy extraction efficiency and optical damage threshold than the ns usually used in standard design. In this scheme we will demand only a compression ratio of 1000, nowadays not too demanding. With such a long pulse for extraction, based on previous experiments [1], 10mJ per pulse and per LMA fiber could be obtained. Therefore, the generation of a 70 kJ, 10ps pulse with good wavefront quality, will require the coherent addition of 10^7 fiber outputs. To reach the highest power density, the fiber outputs will have to be coherently combined. Two approaches can be adopted: a) phase diversity used in astronomy [7] and b) lateral shearing interferometry [8].

3. Discussion
3.1 ICF physics

This new laser design, based on a very large number of diode pumped fibers for the compression pulse, meets perfectly well the specifications requested for Inertial Confinement Fusion, not only from the point of view of the driver efficiency and repetition rate but also for the ICF physics and the reactor design. The three major concerns for ICF are the good uniformity of irradiation, the high efficiency of the laser-plasma coupling and the limitation of the number of high energy electrons. The main challenge in direct drive ICF is how to prevent or at least reduce seeding and growth of the Rayleigh Taylor (RT) hydrodynamic instabilities. This puts stringent requirements on laser irradiation non uniformities as well as target outer-surface roughness and inner interfaces.

The very large number of beams of high quality and reproducibility is very favorable to irradiation smoothing of the target by overlapping the focal spots and should lead to non-uniformities with ΔI/I < 1 % requested to limit the hydrodynamic instabilities. This also induces natural spatial and temporal incoherence of the overall irradiation on target. The fibers will be installed around a spherical geometry, so irradiating the target with different directions, which provides spatial incoherence. Temporal incoherence comes from the very large Yb:glass gain bandwidth, Δν~10^{13}Hz.

Each fiber could work at a slightly different wavelength compared to the others by adjusting the pumping, and with small differences in the fiber lengths, the channels will have different phases to provide the most incoherent illumination on target. Further more, it will be possible to install the fibers in such a way that the polarization of the different beams will be random. Complete spatial, temporal and polarization smoothing is thus naturally produced because of the very large number of beams.
Thanks to this complete beam smoothing, the driver wavelength should not need to be in the UV. Simple KDP crystals could produce the $2\omega$ light at the output of the fibers with a good efficiency (>80%). A sketch view of what the fusion chamber would look like is shown in Fig. 1.

3.2 Advantages for a fusion reactor

The proposed fiber driver provides maximum and independent control on the wavefront, pulse duration, pulse shape, timing, making possible reaching the highest gain. The massive manufacturing will be amenable to a cheaper facility with an easy upkeep. Fibers are especially promising to real world applications due to their superior efficiency, robustness, thermal management, integrability, beam quality (single mode), and cost.

All the pumping of the fiber can use standard single-mode laser diodes from the telecom industry. These diodes are very reliable, with expected lifetime of ~10⁶ hours (>10 years of continuous operation). Such lifetimes would make such a laser systems virtually maintenance-free, saving significant operation costs for such a facility. In addition the power could be transported without virtually any losses, to the interaction chamber by low loss fibers. Laser and target chamber would be virtually decoupled. The system will be environmentally stable, mildly sensitive to alignment, and timing. It will be well adapted to massive manufacturing that should drive the cost down and the laser reliability up.

4. Conclusion

We have presented a new design of a fusion driver based on multiple diode pumped fibers, that we call FAN for Fiber Amplification Network. This system will use the well established fiber technology, will be rugged and well adapted to industrial environment. The proposed source would be very efficient (>50% wall plug efficiency) and could deliver simultaneously 200 kJ of nanosecond pulse and 100 kJ of picosecond pulse. The laser characteristics are well adapted to ICF requirements, with high efficiency, spatial and temporal incoherence, with adjustable temporal and pulse shape. Finally, this concept based on massive manufacturing of inexpensive parts should lead to a laser driver with an attractive construction and upkeep cost.

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