Feasibility of fiber lasers for laser fusion

A. Galvanauskas[1], T. Zhou[2], A. Rainville[1], C. Pasquale[1], M. Whittlesey[1], Y. Jing[1], R. Wilcox[2], Q. Du[2], J. van Tilborg[2], E. Esarey[2], C. Geddes[2]

[1] University of Michigan, G. Mourou Center for Ultrafast Optical Sciences
[2] Lawrence Berkeley National Laboratory, Accelerator Technology and Applied Physics Division

The feasibility of using nanosecond pulsed fiber lasers for driving inertial fusion has been first considered more than 10 years ago [1]. Interest in exploring the potential of using such lasers for this application was driven primarily by the high wall plug efficiencies characteristic to fiber lasers. The challenge of limited energies from individual fiber lasers was addressed by proposing a large number of very compact and monolithically integrated fiber laser modules, arranged into a fiber amplification network (FAN), with their output beams incoherently combined on the laser-target. At that time it was assumed that the highest achievable nanosecond-pulse energy per fiber channel is limited to approximately 10mJ. Therefore, for 1-10 MJ energies required for the laser fusion, the total number of the fiber laser channels would be on the order of $10^8 – 10^9$. Considering that an inertial fusion target is usually driven by >100 separate laser beams, each from an individual laser driver, then each such driver would be a FAN consisting of approximately 10^6 - 10^7 pulsed fiber laser channels. Although assembling this large number of fiber channels in a single system is certainly a daunting technological challenge, but a monolithic compact integration of each individual channel is expected to significantly mitigate this problem [1]. Commercial incoherently-combined fiber laser systems containing ~10^2 of monolithically-integrated individual high-power fiber lasers are available [2]. Therefore, assuming that with further investments systems with 10-100 larger number of channel per FAN could be developed, laser drivers with up to ~10^4 channels should be possible. However, much larger numbers per driver might be prohibitively difficult.

We are proposing to revisit this approach, since continuous development in large core fiber technology have enabled much higher energies, approximately 100 mJ per single-core fiber amplifier [3]. Furthermore, multicore fiber structures are also possible [4] that could enable further increase of pulse energy for a fiber laser to approximately 1J, and potentially even higher. Using these advances in fiber technology could significantly reduce the projected number of individual fiber laser channels required to reaching 1MJ-10MJ energies, down to approximately $10^4 – 10^5$ channels respectively per driver built as an incoherently combined FAN system. As it was indicated in the previous section, these lower channel numbers could be technologically feasible.

Use of short-pulse fiber lasers for fast ignition was also proposed in the same paper [1]. This approach faces two technical challenges. First, this would require a coherent combination of all the output beams from a fiber amplification network, technologically a much more challenging problem than their incoherent combination. The further challenge is that, although pulse energies required for fast ignition are much smaller than those for driving inertial confinement fusion (1kJ to 10kJ vs >1MJ), the amplified energy of ultrashort pulses in fiber amplifiers is limited by the onset of nonlinear effects and thus requires use of chirped pulse amplification technique (CPA). Since fiber CPA can only extract a small fraction (on the order of few percent) of all the energy stored in a fiber amplifier, this leads to the need to coherently combine a very large number of optical beams. Assuming that ~1mJ can be extracted from a large-core fiber CPA system, then the required number of spatially coherently combined channels is on the order of $10^6 – 10^7$, for 1kJ - 10kJ respectively. This is similar to the number of channels that were projected in the same paper for fiber-based inertial fusion drivers, but would be even more difficult to achieve due to the need of coherent combining this large number of beams.

Fortunately, since the time of publication of [1] a new technique has been proposed, demonstrated experimentally, and is currently being developed further for future laser-plasma accelerator drivers, which allows to overcome fiber CPA limitations, and thus to significantly reduce the number of channels in an ultrashort pulse fiber laser array. This is the coherent pulse stacking amplification (CPSA) technique [5], which currently allows to extract more than 90% of the stored fiber energy, and has demonstrated approximately 10mJ per fiber amplification channel [6] using monolithic-integration compatible large core specialty fibers. With the further development of large core fiber technologies as well as CPSA technique it is conceivable to extend these energies into 20-50mJ per channel. With these advances fiber laser array sizes for fast ignition applications could also be reduced to the range of $10^4 – 10^5$ (for 1kJ – 10kJ energies respectively) fiber laser channels. As it was discussed earlier, using current commercial monolithically integrated multi-fiber laser systems as a benchmark one could project that reaching 10^4 of parallel laser channel could be potentially feasible.

In conclusion, recent and ongoing technological advances in high energy generation from specialty large core fibers, as well as development of a novel time-domain coherent combining techniques makes it possible to imagine using these advanced fiber laser technologies for developing efficient laser drivers for inertial fusion as well as for fast ignition. The key is to reduce the number of combined fiber amplifier channels to a more practically feasible level of ~10^4 channels per driver.

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