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High average power femtosecond laser driver for plasma accelerators by compression of spectrally broadened high energy Yb:YAG laser pulses

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Motivation and goals

Laser driven plasmas can generate accelerating gradients that are several orders of magnitude greater than conventional accelerators based on RF technology. This makes laser-plasma accelerators an attractive candidate technology for future colliders as well as for many shorter term accelerator applications that include compact bright x-ray and gamma ray sources. However, the laser parameters required significantly surpass the state-of-the-art of ultrashort pulse lasers. A DoE workshop on Laser Technology for Accelerators [1], and a more recent workshop on Laser Technology for k-BELLA and beyond [2] defined the necessary laser parameters for advanced acceleration for different applications. In particular, for laser wakefield electron acceleration to multi-GeV energies, femtosecond pulses with multi-Joule level energy are necessary. A femtosecond Ti:Sapphire laser producing 0.85 PW pulses has been used to demonstrate 8 GeV electron beams [3]. However, the driving laser in this demonstration experiment was limited to 1 Hz repetition rate. To date, the highest repetition rate petawatt-class lasers have operated at repetition rates of several Hz [4-7]. The majority of the applications require repetition rates and average powers that that are 1,000 times higher, and beyond. For example, a "Type II" [1] femtosecond laser delivering 3 J pulses of < 100 fs at 1 kHz repetition rate is needed to drive a 1 GeV laser plasma accelerator testbed as the next step in the development of practical laser plasma accelerators. In the medium term (10-15 years) a 30 kW femtosecond laser will be needed for a prototype collider module and for high average power radiation sources, with additional increases in average power in the long term. A realistic approach to efficient direct generation of Joule sub-100 fs lasers operating at multi-kHz repetition rate relies on diode pumped cryogenically cooled Yb:YAG as the amplifier gain medium. Its small quantum defect and high heat conductivity are the basis for effective thermal management and high wall plug efficiency. The technology main downside, the intrinsically narrow amplifier bandwidth, can be overcome by subsequent spectral broadening and compression in long, large ID hollow-core fibers followed by dispersion control.

Generation of sub-100 fs Yb:YAG multi-Joule laser pulse by spectral broadening in hollow-core fibers

Cryo-cooled Yb:YAG laser technology demonstrated by Colorado State University and XUV Lasers [8,9] has already demonstrated the generation of >1 J pulses at 1 kHz repetition rate (kilowatt average power) with a pulse duration of < 5ps duration. This approach to generating high energy, picosecond duration pulses at high repetition rates relies on cryogenically-cooled Yb:YAG active mirrors [8]. Yb:YAG, which has a high quantum efficiency and that can be readily pumped with very efficient commercially available diodes offers the possibility for developing a compact and efficient driver for advanced accelerators. Cryogenic-cooling of Yb:YAG offers the advantage of significantly increased thermal conductivity, improved thermal expansion coefficient and thermo-optic coefficients by factors of 4 and 7, respectively [10]. These enhancements are crucial as they largely determine the thermal refractive response of the material, which often is the effect that limits the achievable average power. The improved thermal parameters at cryogenic temperatures allows to use a larger amplifier thickness, with the advantage of increased pump absorption that reduces the complexity of the pump optics. Additionally, the narrower linewidth leads to an increase of the stimulated emission cross section and the corresponding decrease of the saturation fluence. This allows for efficient energy extraction in a low number of passes at fluences which do not cause damage. Furthermore, at cryogenic temperature, Yb-doped media function as four level laser systems, allowing for more efficient high energy amplifier operation. The thick disk active mirror geometry employed in these amplifiers develops mostly longitudinal thermal gradients that reduce the thermal lensing encountered in cylindrically-cooled gain geometries. Its comparatively small thickness limits the maximum temperature in the gain region while its moderate diameter-to-thickness ratio has the advantage of limiting the transverse gain, which diminishes amplified spontaneous emission (ASE) depletion of the amplifier stored energy.

However, the gain bandwidth of Yb:YAG at cryogenic temperatures limits the pulse width of these cryogenically cooled kW average power lasers to > 3 ps. Spectral broadening and compression of Yb:YAG ps pulses in long, large ID hollow-core fibers provides a path forward for the direct generation of sub-100 fs high energy laser pulses at high average powers. Very recently, this technique has been successfully demonstrated at the 50 mJ energy level for 220 fs input pulses [11]. In another experiment, record high compression factors of 33 have been achieved in a single compression stage [12]. A prototype for average power scaling has been tested at the half kW average power level. A collaboration between Colorado State University and few-cycle is currently investigating how to combine all the above performance aspects (high energy, large compression, high average power) in one experiment by propagation of Joule-level Yb:YAG laser pulses in gas-filled hollow-core fibers (Fig.1) with promising results. In a first test run, 0.7 J, 7 ps pulses have been coupled to a HCF and a portion of the 0.5 J output was compressed to 240 fs at 10 Hz repetition rate. These successful preliminary tests prove that cryo-cooled Yb:YAG lasers combined with subsequent HCF spectral broadening and chirped mirror compression are a promising technology for efficient generation of sub 100 fs pulses at high peak and average powers, respectively, required for LPA applications.

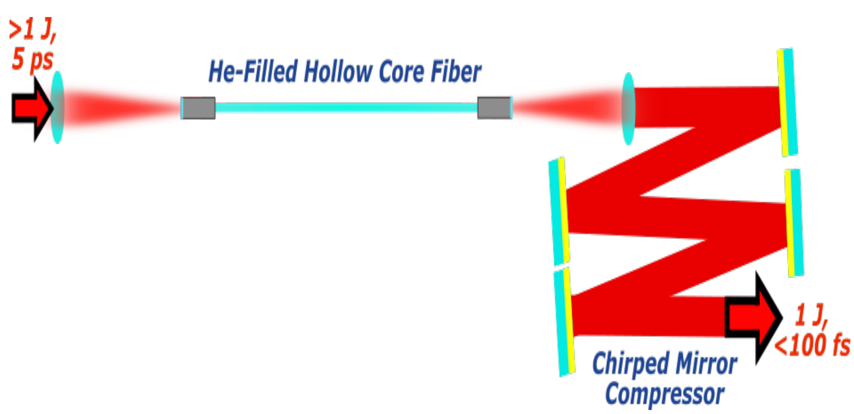

Figure 1. Conceptual diagram of the high pulse energy, hollow core fiber spectral broadening and pulse compression testbed.

Summary and Path forward

Cryogenically cooled Yb:YAG amplifier high pulse energy technology, that has been successfully demonstrated for 1 J pulses at the 1 kW laser average power level, combined with spectral broadening in gas filled hollow-core fibers and post-compression is a promising method to efficiently generate the short high energy pulses at the high repetition rates necessary for advanced laser-driven accelerators. The currently achieved ~ 30 fold pulse compression can be further enhanced by using longer fibers, while the use of HCFs with larger ID should allow for the compression of higher energy pulses. One intrinsic advantage of energy scaling with larger inner diameter (ID) fibers is that the transmission increases ~ID^3. This will enhance output energy and ease thermal management at the same time.

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