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Multi-GW Peak Power Scaling in a Multi-pass Cell by Divided Pulse Scheme.

Henrik Schygulla[1,2], *Nayla* Jimenez[1,3,4,*], *Yujiao* Jiang[1], *Ingmar* Hartl[1] and *Marcus* Seidel[1,3,4]

[1] Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany
[2] University of Hamburg, Department of Physics, Notkestraße 9-11, 22607 Hamburg, Germany
[3] Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
[4] GSI Helmholtzzentrum für Schwerionenforschnung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany

Abstract. Multi-pass cells, known for their efficient spectral broadening, currently face a challenge in their peak power scalability. To address this, we implemented a strategy where the input pulse was split into 8 replicas, resulting in an increased pulse energy following nonlinear compression. The used laser delivered 208 fs pulses at 1030 nm, with pulse energies reaching up to 140µJ. Using 3 calcite crystals, the input pulse was divided and passed through the MPC, achieving a spectral broadening down to a 40 fs bandwidth limit. Subsequently, the replicas were recombined using an identical set of crystals and compressed via chirped mirrors. FROG measurements revealed a duration of 43 fs. The recombination losses amounted to less than 5 % of the output energy. This method is particularly attractive and cost-effective for spectral broadening of ultrafast lasers with adjustable repetition rate.

1 Background

Herriott-type multi-pass cells (MPCs) have emerged as a robust and versatile platform for compressing high-power lasers with hundreds of femtosecond or picosecond pulse durations [1,2]. Most of the reported MPC experiments have been performed with Yb-ion based lasers. These deliver radiation with fixed average powers of tens to hundreds of watts, but with flexible repetition rates and pulse energies. The variable peak powers are challenging for post-compression stages, because of the nonlinear nature of spectral broadening. Even more complex are setups that require synchronization to a second pulsed source.

Adjusting the optical pathlength through the MPC to the input peak power, as typically done to prevent mirror damage or ionization [1], would result in a major timing offset that cannot be easily compensated by standard delay lines. The described setting is given at FLASH, the free-electron laser facility in Hamburg, Germany. In the last couple of years, about 80 % of the user experiments used a pump-probe scheme where ultrafast XUV- or soft-X-ray radiation was overlapped in space and time with ultrashort pulses from an optical laser. In addition, the facility is about to replace the previously used optical parametric amplifiers with MPCs [3,4]. Eventually, the condensed matter community preferably works with µJ-energy pulses at 1 MHz repetition rate, while the gas-phase community typically prefers 100 kHz repetition rates and higher pulse energies. To comply to these requirements and to minimize preparation times for the user experiments, wide-range pressure tunability of gas-filled MPCs was initially envisioned [4]. Here, we use temporal pulse division and coherent recombination with birefringent crystals [5-7] to preserve spectral broadening in a bulk MPC despite two, four or eight-fold increase of input peak power.

2 Methods

For a proof-of-concept demonstration, we used a Light Conversion Pharos laser, which emitted 208 fs pulses at 1030 nm central wavelength. The experimental setup is shown in Fig. 1. After polarization cleaning by a thin-film polarizer (TFP), a sequence of three a-cut calcite crystals divided a single 140 µJ pulse into a train of eight pulses.

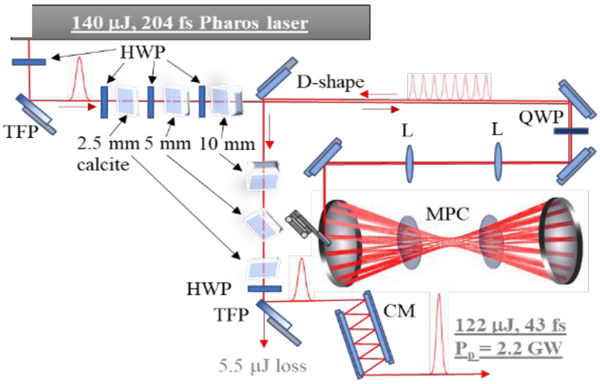

Fig. 1. Experimental setup. TFP: thin-film polarizer, HWP: half-wave plate, QWP: quarter-wave plate, D-shape: D-shaped mirror, L: lens, MPC: multi-pass cell, CM: chirped mirror

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[*] Corresponding author: nayla.jimenez@desy.de

We placed a half-wave plate (HWP) in front of each calcite to project one half of the optical power on the fast and one half on the slow axis of the birefringent crystals. The refractive index difference of both axes yields a temporal walk-off of 544 fs/mm. Using crystals of 2.5 mm, 5 mm and 10 mm thickness hence resulted in 1.36 ps mutual delays between the pulses and an alternating s- and p-polarization. We used highly reflective dielectric mirrors which exhibit different penetration depths into their multi-layer structure for s- and p-polarization at oblique angle of incidence. To compensate for the consequent walk-off, we inserted a quarter-wave plate (QWP) in front of the mode-matching telescope. It rotated the polarization axis by 90° after the laser beam passed when entering and coming from the MPC, and thus compensated most of the mirror-induced path difference. Moreover, we used a second set of calcite crystals in reverse order for the recombination of the pulses. All calcites were mounted on magnetic bases, which enabled easy switching between single, double, four and eight pulse configurations. The 396 mm long MPC was configured for 15 roundtrips and the least angular advance on the MPC mirrors (2π/15). Two 1 mm thin anti-reflection coated silica windows were used as Kerr media. The mode-matching telescope was also used for recollimation after the MPC. Ingoing und outcoming beam were separated by a D-shaped mirror. After pulse recombination, a HWP and a TFP were used for polarization cleaning. For compression of the pulses, the beam was 26-times reflected from chirped mirrors (CMs) with -200 fs^2 group delay dispersion per bounce.

3 Results

The nonlinearity in the MPC was adjusted such that a single 17.5 µJ pulse was spectrally broadened to a Fourier transform limit (FTL) of 40 fs. There was no noticeable difference between the obtained bandwidths with a single pulse and a train of eight pulses with 140 µJ total energy. The broadened spectrum is shown in Fig. 2a. We used a home-built second harmonic FROG to measure the compressed pulse duration. The retrieved spectrum and the 43-fs short pulses are shown in Fig. 2a and b. The pulse was retrieved with 0.5 % FROG error from the raw trace shown in Fig. 2c. We investigated the additional losses that the temporal stacking technique introduced. Since we used orthogonal linear polarizations to divide the pulses, polarization cleaning after recombination revealed the first type of losses. Less than 5 % of the power transmitted through the recombination stage was filtered by the polarizer. We note that nonlinear depolarization occurs also in single pulse operation, and thus the 5 % present an upper limit of the excess losses introduced by the birefringent crystals. The second type of losses concern the emergence of side pulses due to imperfect recombination. The strongest side pulse was visible at about 1.36 ps delay from the main pulse. We centred a FROG scan at this delay to estimate the power of the strongest pedestal. Fig. 2c and d were taken with the same spectrometer integration time. The colour bar scales show that the dominant side pulse is at least two orders of magnitude weaker than the main pulse. By integrating over the spectrum, we deduced that the side pulse contained only 0.6 % of the main pulse power. This value is also in good agreement with the modulation depth of the fast oscillations in the blue spectrum shown in Fig. 2a. Overall, 122 µJ of the initial 140 µJ were transmitted through the setup. Under consideration of the pulse shape from Fig. 2b and the side pulse energy, we deduce an output peak power of 2.2 GW, ranging among the highest for bulk MPC spectral broadening [8-10].

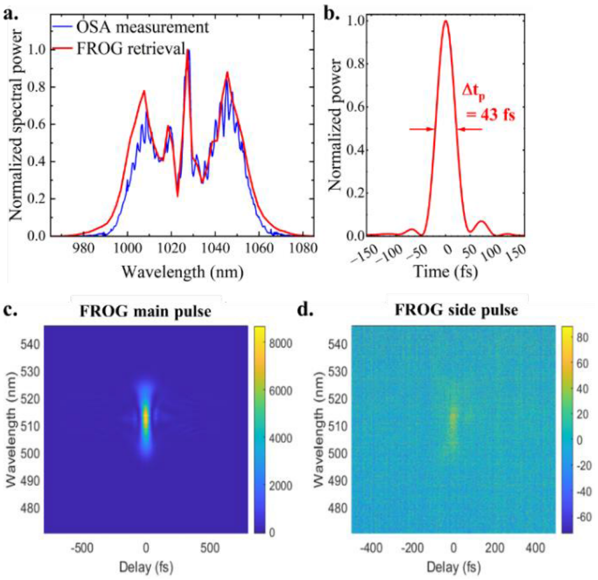

Fig. 1a. Normalized spectra of the broadened pulses measured with an optical spectrum analyzer and retrieved from FROG. **b**. Compressed pulse after recombination retrieved by FROG. **c.** Raw data of FROG trace around the main pulse. **d.** Raw data of FROG trace around the dominant side pulse.

4 Conclusions

We have demonstrated a divided pulse spectral broadening scheme based on temporal stacking and coherent recombination by birefringent crystals. Since these crystals can be readily inserted and removed from the setup, the approach presents an excellent solution for spectral broadening of average power-limited lasers with adjustable repetition rates. Moreover, the demonstrated nearly eight-fold peak power enhancement relative to single pulse operation is highly attractive for nonlinear post-compression of energetic pulses which usually require impractically long MPCs [11].

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