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# 880 nm, 22 fs, 1 mJ pulses at 100 Hz as an OPCPA front end for Vulcan laser facility

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## ABSTRACT

In this paper we present a picosecond front end developed for a fully OPCPA based new PW system for the Vulcan laser facility. The system delivers 22 fs pulses with 1 mJ pulse energy at 100 Hz repetition rate.

## 1. Introduction

The PW beamline of the Vulcan laser facility has been operating since 2003 and is used to study laser-matter interactions under extreme conditions. This beamline delivers laser pulses with an energy of 500 J and 500 fs pulse duration with a repetition rate of one shot every 30 min [1]. In order to expand the capabilities of the facility, we are developing an auxiliary PW beamline, where we will deliver 30 fs pulses with a pulse energy of 30 J with one shot every 5 mins. The two beamlines will be capable of operating together, enabling the possibility of pump-probe experiments where the probe could be electrons or X-rays generated by the new beamline.

There are two main techniques for generating intense, ultrashort high-energy laser pulses: Chirped Pulse Amplification (CPA) [2] in a laser gain medium or Optical Parametric Chirped Pulse Amplification (OPCPA) [3,4], where laser pulses are amplified in a nonlinear crystal. The main advantages of the OPCPA method are the high single pass gain, and lower thermal effects as well as the ability to support amplification of a broadband spectrum [5].

Currently, most large scale facilities are based on CPA technology or CPA with an OPCPA front end [6]. While NIR OPAs and OPCPAs have been successfully used for higher repetition rate and mJ level systems [7–11], only a few large scale systems have started exploring the capabilities of using only OPCPA technology [12–14]. Our system [13] is designed to deliver 30 fs pulses with 30 J pulse energy. Our new PW beamline consists of ps and ns front end followed by two power amplifiers. An ultra-broadband Ti:Sa oscillator is stretched up to 3 ps in a double pass bulk stretcher consisting of two 50 mm blocks of BK7 glass, then these chirped pulses are used as a seed for the parametric amplifiers. The picosecond front end, which will be discussed in this paper, is pumped by two Yb regenerative amplifiers and after four amplification stages we achieve a pulse energy of 1 mJ. Afterwards, amplified ps pulses will be further stretched up to 3 ns and sent for amplification in the ns stages. The ns stages are divided into two parts: ns front end, which consists of the first three stages and the two power amplifiers. The ns front end will be pumped by a 4.5 J, 10 Hz Nd:YAG laser, while the two power amplifiers will be based on Nd:glass in-house built pump lasers, of 30 J and 200 J respectively, and working at the repetition rate of one shot every 5 mins. The second power amplifier will be one of the long pulse beamlines of the Vulcan laser facility. Finally, the output of the OPCPA will be compressed in a grating compressor with an estimated transmission of 60%.

From our experience, [15] the front end of high energy systems plays an important role in the overall performance of the system and defines pulse contrast, which is an important parameter for our laser-matter interaction experiments. In this paper we present a picosecond front end for the new Vulcan PW beamline, which is fully based on OPCPA technology. The system is designed to deliver sub 30 fs pulses with a pulse energy of 1 mJ centered at 880 nm. Currently the front end is delivering broadband pulses centered at 880 nm with a pulse energy of 1 mJ at a repetition rate of 100 Hz. We also show pulse compression down to 22 fs with a long term stability of 1.4% rms.

## 2. The choice of nonlinear crystals

As this system is a front end for a large OPCPA system, it is important to ensure the capability to amplify broadband pulses from

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**Table 1**
Summary of properties of nonlinear crystals.

| | BBO | LBO | DKDP |
|---|---|---|---|
| Transmission, nm [16] | 185–2600 | 160–2600 | 200–2000 |
| Nonlinear coefficient, pm/V [16] | 2.01 | 0.83 | 0.25 |
| Walk off, mrad [16] | 56 | 7.4 | 25 |
| Noncollinear angle, deg | 2.3 | 1.6 | 1 |
| Amplification bandwidth, nm | 350 | 350 | 200 |
| Damage threshold, GW/cm$^2$ [17] | 10 | 19 | 8.4 |
| Maximum crystal size, cm | 2.5 | 10 | 40 |

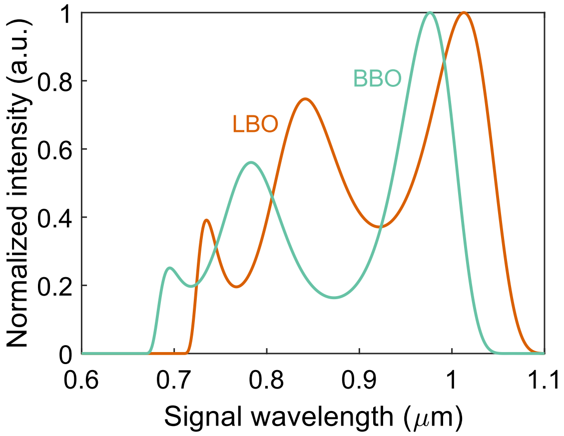

**Fig. 1.** Normalized amplification curves for BBO and LBO crystals achieving the same signal gain.

μJ to J level. Only a handful of nonlinear crystals can be grown large enough to support beam sizes of tens of centimeters. To begin with, we have identified 3 commercially available crystals: BBO, LBO and DKDP. Parameters of these crystals are shown in Table 1, data here is for the pump at 515 nm and signal at 880 nm.

DKDP is the only crystal, which can be grown with apertures up to 40 cm [18], but the nonlinear coefficient and the damage threshold are lower than LBO and BBO. Since the optimum pump beam size for efficient amplification within the Laser Induced Damage Threshold (LIDT) fluence on the crystal at the final amplification stage is about 10 cm, DKDP shows no advantages over the other two crystals.

BBO is a conventional crystal, successfully used for NIR OPAs [7–9, 19], while LBO has recently started to be implemented into broadband NIR OPA systems [10,11,14,20]. BBO features higher $d_{eff}$, but the crystal size is limited to 2.5 cm. While it is a good candidate for smaller OPA stages, LBO is required for the large amplifiers. The amplification curves in both crystals are shown in Fig. 1. Here, amplification takes place in 5 mm BBO and 11 mm LBO, both crystals are pumped by 515 nm pump, and pump intensity on the crystal is 50 GW/cm$^2$. The different crystal length of LBO compensates for its lower $d_{eff}$. The internal noncollinear angle for BBO is 2.4 and for LBO is 1.6 deg, also the walk-off is seven times smaller in LBO, thus longer crystals can be used maintaining a good overlap between the pump and signal beams. Both LBO and BBO crystals are suitable for broadband amplification in the spectral region of 800–960 nm.

At the time of project design, there were a very small number of LBO-based broadband OPA systems [20] in the NIR, thus the choice was made to use all LBO crystals in order to verify the broadband amplification and usage of the crystal at the large stages.

## 3. The lay out of the set up

The set up of the ps front end is depicted in Fig. 2. Here the seed source is an ultrabroadband Ti:Sa oscillator (Venteon Dual, Laser Quantum): 80 MHz, 2 nJ, 5 fs, 650–1150 nm. The output pulses from the oscillator are split into two parts, the spectral part 650–970 nm is selected to be the seed for our optical parametric amplifiers, while the residual infrared part is left for the possibility of seeding pump lasers. However, in the current configuration, the seed source for the pump lasers is a dual-output Yb fiber oscillator (Amplitude), which is then electronically synchronized with the Ti:Sa oscillator. To pump our OPAs, we use two pump lasers, both Yb-based regenerative amplifiers. The first two stages are pumped with the second harmonic (SHG) of a Yb:KGW regenerative amplifier (S-Pulse, Amplitude: 100 Hz, 1.7 mJ, 16 ps, 1030 nm) and the last two stages are pumped with the SHG of a Yb:YAG regenerative amplifier (Magma 25, Amplitude: 100 Hz, 24 mJ, 26 ps, 1030 nm). In both cases SHG is generated in 2 mm BBO crystals with an efficiency of 30% for the S-pulse and 50% for Magma 25, which corresponds to 470 μJ and 12.5 mJ respectively.

The output pulses of the Ti:Sa oscillator have a pulse duration of 5 fs. In order to match signal pulse duration to pump pulses, we stretch our signal in an all-bulk stretcher. The stretcher consist of two identical blocks of 5 cm BK7. It is set at Brewster angle and in a double-pass configuration, which minimizes the angular and chromatic dispersion. 20 cm of BK7 introduces 7400 fs$^2$, thus signal is stretched to 3 ps. The ratio of pulse durations between the signal and pump pulses is kept to be around three in order to ensure the efficient amplification of all the spectral components of the chirped signal pulse [21].

## 4. System performance

### 4.1. Amplification stages

All the OPA stages in the system use LBO crystals. In order to achieve the broadest phase matching conditions, the noncollinear configuration is used and an internal angle between pump and signal pulses is set to 1.6 deg. Indeed, a broadband amplification was achieved and 220 nm spectrum is being amplified (see Fig. 3).

470 μJ pump pulses are split between OPA1 and OPA2, with 130 μJ used to pump OPA1 and 340 μJ used for OPA2. For both stages, the pump beam is about two times smaller than the signal beam and is about 1.3 mm FWHM. The energy fluence of the pump beams at the crystals is 0.01 J/cm$^2$ for OPA1 and 0.035 J/cm$^2$ for OPA2. In order to maintain the similar size ratio between the two stages, the signal beam is imaged into the 2nd stage by using an achromatic telescope consisting of two lenses (positive and negative of equal focal length) and an off-axis parabola mirror with the ROC being twice the focal length of the lens; all the elements are separated by one focal length. The total pump-to-signal conversion efficiency is 5%, and at the output of the OPA2 we have an amplified signal with pulse energy of 25 μJ.

Afterwards, the output of OPA2 is sent to the Acousto-optic Programmable Dispersive Filter (AOPDF) (Dazzler, Fastlite) and the diffracted beam is later amplified in OPA3 and OPA4. The transmission of the Dazzler was estimated to be about 10%, thus the seed for the OPA3 is about 2–3 μJ. Between the Dazzler and the OPA3, the signal beam size in increased by about four times and is equal to 5 mm FWHM. The pump here is 4 mm FWHM. In between the OPA3 and OPA4, we again have a two times magnifying achromatic telescope and the signal size there is 8 mm FWHM and pump is 7 mm FWHM. The energy fluences of the pump on the crystals are 0.02 J/cm$^2$ and 0.03 J/cm$^2$ for OPA3 and OPA4 respectively.

A Dazzler is inserted between the OPA2 and OPA3. Since our model is not well adapted to support the 200 nm bandwidth, we cannot fully exploit the Dazzler's capabilities. The uncompensated positive dispersion of the $TeO_2$ crystal is high enough to stretch our signal pulses up to 10 ps. This means the pulse duration of the second pump laser has to be adjusted. In order to maintain a similar ratio to OPA1 and OPA2, pump pulses are stretched to 26 ps.

The SHG of the Magma 25 delivers pulses with 12.5 mJ energy. OPA3 is pumped by 1.5 mJ pulses and the signal is amplified up to 30 μJ, the remaining 11 mJ of the pump is used to pump OPA4, where the

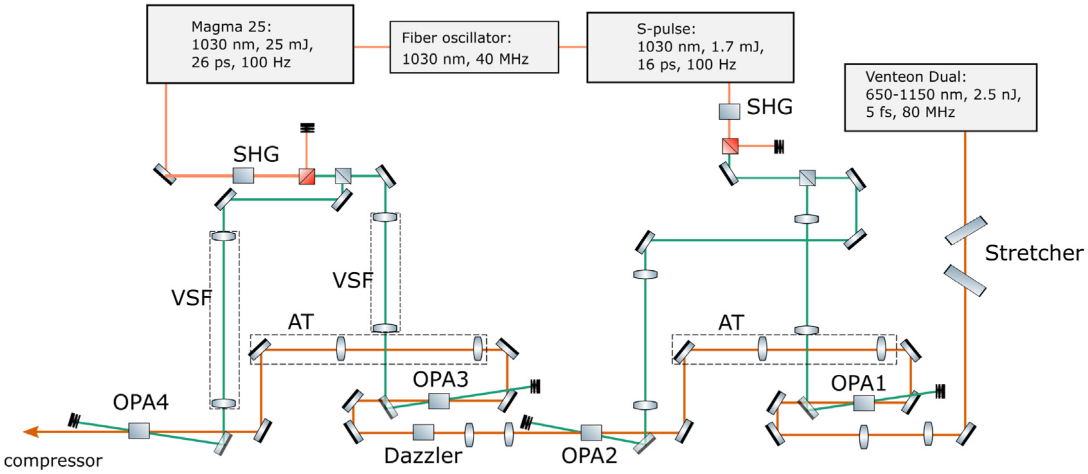

**Fig. 2.** The layout of the ps front end of the new Vulcan PW OPCPA beamline. SHG — second harmonic crystal, VSF — vacuum spatial filter, AT — achromatic telescope.

**Table 2**
Summary of amplification in all OPA stages.

| | Crystal length, mm | Pump energy | Amplified signal | Gain | Efficiency, % |
|---|---|---|---|---|---|
| OPA1 | 20 | 130 μJ | 1.5 μJ | $10^3$ | 1 |
| OPA2 | 19 | 340 μJ | 25 μJ | 15 | 7 |
| OPA3 | 15 | 1.5 mJ | 25 μJ | 10 | 2 |
| OPA4 | 20 | 11 mJ | 1 mJ | 45 | 9 |

signal is amplified up to 1 mJ with pump-to-signal conversion efficiency of 9%. The total pump-to-signal conversion efficiency for these two stages is 8%. A summary of amplification results for all the OPA stages is provided in Table 2.

### *4.2. Reducing the level of superfluorescence*

One of the parasitic effects in optical parametric amplifiers is superfluorescence (SF), which can significantly reduce the level of temporal contrast required for high intensity experiments. In our system, pump beams are smaller than the signal beams, so they act as a soft aperture and ensure that pump energy is used for signal amplification rather than generating superfluorescence. Furthermore, the ratios of all the pump energies were chosen to minimize superfluorescence and maximize the efficiency of the system. Two devices were used to measure the level of SF: a spectrometer and a power-meter with minimum measurable value of 2 mW. Here no SF was detected, which indicates that the SF level is lower than 1.5%. Both measurements were done at the output of the system after blocking the signal before the OPA1.

### *4.3. Pulse compression and stability*

In order to test the compressibility of the output of the system, we have used a single-grating compressor. Even though a grating compressor allows us to compensate for the positive dispersion of the signal, it can only compensate the negative third order dispersion. This issue can be solved by adding a prism compressor or an AOPDF. We have chosen the latter and placed the Dazzler between the stages of OPA2 and OPA3.

The compression results are shown in Figs. 4 and 5. We achieve a pulse duration of 22 fs, and our spectrum supports 14 fs transform limited pulses. The principal reason preventing us from reaching the transform limit for our pulses is that the AODPF which we have in our system is not capable of supporting such a broadband spectral bandwidth and a part of the spectral phase stays uncompensated.

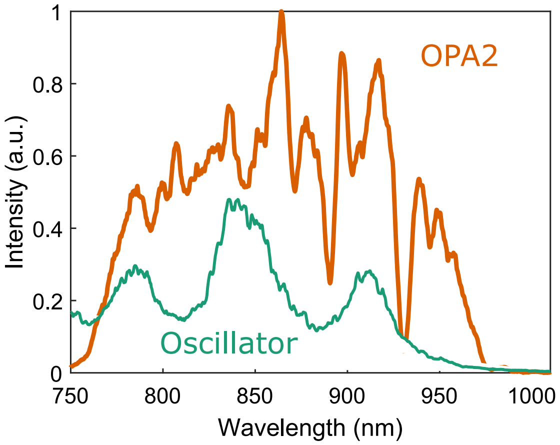

**Fig. 3.** Spectrum of the Ti:Sa oscillator and the output of the OPA2: 220 nm broadband spectrum is amplified.

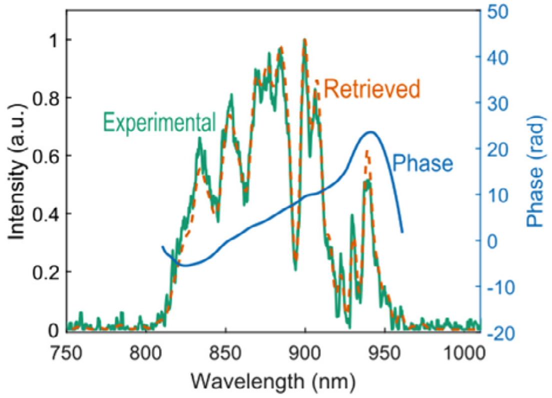

**Fig. 4.** Measured and retrieved spectrum together with the spectral phase of 22 fs pulse.

The stability of the pulse duration correlates with the bandwidth of the amplified spectrum and thus is strongly influenced by the timing jitter between signal and pump pulses. Fig. 6. shows the stability of pulse energy together with pulse duration and transform limited pulses, which also corresponds to the stability of the spectral bandwidth. Here the pulse duration was below 20 fs, with the pulse energy of 1 mJ, but the shorter pulse duration was achieved at the cost of the quality of the temporal pulse profile. The pulse energy and pulse duration stability are 1.39% rms and 1.41% rms respectively.

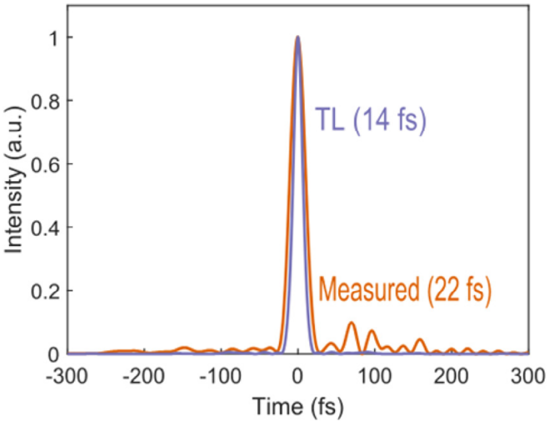

**Fig. 5.** Measured temporal pulse profile (22 fs) and the transform limited pulse profile (14 fs).

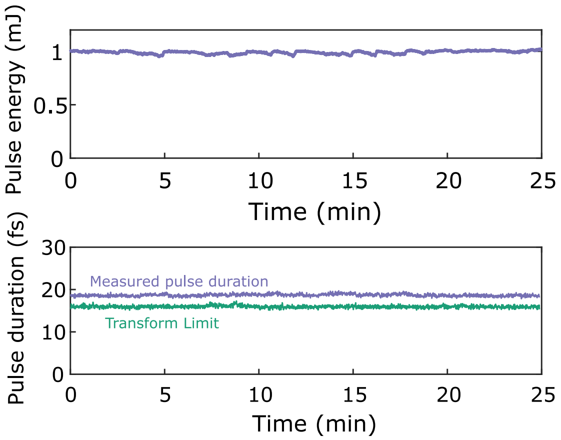

**Fig. 6.** 25 min stability measurement of the pulse energy of the system together with the pulse duration and the transform limited pulse duration (spectral width).

## 5. Conclusions

We present a front end for the new PW beamline for Vulcan laser facility. It is an OPCPA system delivering broadband 1 mJ pulses at 100 Hz repetition rate. The requirements for this front end is to provide 1 mJ pulses with spectrum supporting at least 30 fs pulse duration. Thus, the front end is operating well within the design requirements to be successfully used in further amplification stages of the system. We have demonstrated the compressibility of the output of the system and compressed pulses down to 22 fs, with stability of 1.4% rms.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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