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Review

A Review of Optical Parametric Amplification at the Vulcan Laser Facility

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Abstract: An overview of Optical Parametric Chirped Pulse Amplification (OPCPA) is given as the basis for the next generation of ultra-intense laser systems (>1 × 10^{23} W/cm^2). The benefits and drawbacks of OPCPA are discussed to explain the choice behind the decisions for the direction of the Central Laser Facility's (CLF) upcoming Vulcan 20-20 project. A history of OPCPA use at the CLF is described to surmise the foundation of the confidence in this technology for Vulcan 20-20; a 20 PW user facility for high-intensity plasma physics.

Keywords: OPCPA; Vulcan; DKDP

1. Introduction

In the last twenty years, there has been significant progress in the advancement of optical parametric chirped pulse amplification (OPCPA) technologies. Noteworthy improvements have been achieved across multiple crucial parameters, including enhanced energy output, more precise control over pulse duration, improved temporal contrast, expanded bandwidth capabilities, increased repetition-rates, and heightened overall system stability. This collectively results in more versatile pulses for a range of experimental applications derived from high-peak powers.

OPCPA was pioneered by Dubietis et al. in 1992 [1]. This work employed a type I phase-matched Beta Barium Borate (BBO) crystal to amplify femtosecond laser pulses from a Titanium Sapphire (Ti:Sapph) oscillator with a frequency-doubled Neodymium-doped Yttrium Aluminum garnet (Nd:YAG) laser pump source. A gain factor of 2 × 10^4 was observed, reaching a signal output of 0.9 GW/cm^2, compressed to 70 fs.

This achievement was quickly spread amongst the high-power laser industry with proposed high-peak-power systems [2–4], and in the late 1990s initial experimentation began, with the demonstration of 1.3 TW at the Central Laser Facility (CLF) [5]. The highest achievable peak power then escalated: 3.67 TW in 2002 [6], 16.7 TW in 2003 [7], 100 TW in 2005 [8], 350 TW in 2006 [9], 560 TW in 2007 [10], and 1 PW in 2009 [11].

Naturally, over the past twenty years, technology and knowledge has improved substantially: improved crystal availability [12,13]; spectral shaping and phase control techniques [14–16]; compression from large, high-quality gratings; and high-energy nanosecond pumping availability have all contributed to a dramatic improvement in peak pulse intensities.

A high repetition-rate front end of BBO and Lithium Triborate (LBO) crystals is commonplace in laser system for their simplicity, efficiency, and stability. Most high-peak-power facilities to date follow a similar architecture; a combination of this stable OPCPA front end followed by a Ti:Sapph or Neodymium glass (Nd:Glass) power amplifier [17–21]. The scarcity of reliable, large-aperture nonlinear crystals—as well as the unavoidable parasitic lasing—has historically made high-power OPCPA less feasible [22].

The scaling of crystal sizes has allowed a new era of Petawatt class lasers based solely on OPCPA to start to emerge [23–27], and while the drive to the highest average power

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is dominated by Ti:Sapph systems [28–30], the possibility for pushing the highest peak power (and higher intensities on targets) is only currently feasible through OPCPA, as shown in Figure 1. Recently, the drive to high-peak-power OPCPA is being simulated and developed in various facilities allowing 10s PW, 100s PW, and even EWs [31–38]. While there is growing demand for scaling LBO crystals [13,39,40], this is currently only possible with the largest available crystals: deuterated Potassium Dihydrogen Phosphate (DKDP), which was first found to be a promising OPCPA candidate in 2005 [41], harbouring broadband amplification from frequency-doubled Nedodymium-doped Yttrium Lithium Fluoride (Nd:YLF) lasers [42]. There has also been a growing interest in Petawatt-scaling using Yttrium Calcium Oxoborate (YCOB) [37,43], however these are not typical due to the limited number of suppliers.

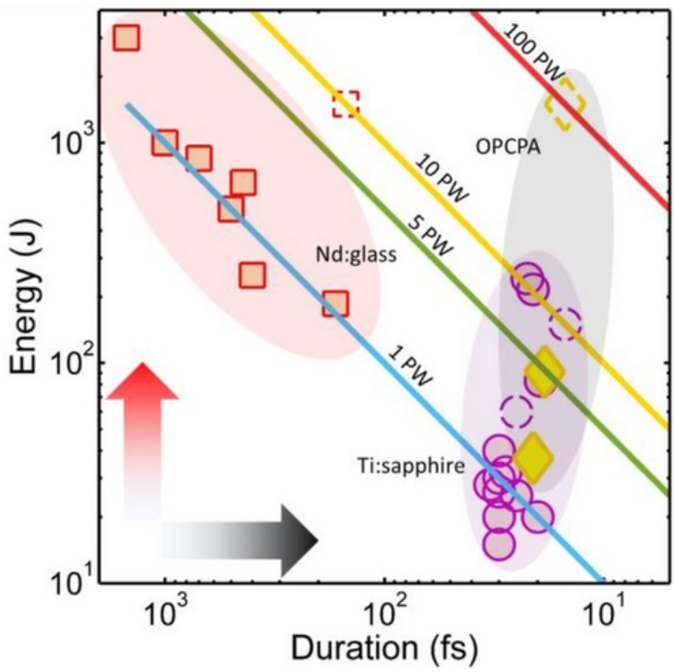

Figure 1. Potential and achieved power of laser pulses based on amplification medium (reprinted with permission) [44]: red symbols represent Nd:Glass systems; purple Ti:Sapph; and yellow OPCPA. Solid and dashed outlines indicate complete facilities and lasers in construction respectively.

Quasi OPCPA technology has recently been investigated, wherein the idler wave is absorbed allowing for a more efficient pump-to-signal conversion ratio, however this becomes less feasible when scaling to larger-aperture crystals [45].

This report focuses on the comparison of OPCPA technology against other amplification methods, and the developments of OPCPA technologies at the Central Laser Facility Vulcan laser, tracing its initial applications in 1997 to the advancements triggering the recently announced Vulcan 20-20 upgrade.

2. Benefits and Drawbacks of OPCPA

Optical parametric amplification (OPA) is the exploitation of the nonlinear properties of crystals to instantaneously transfer energy from a high-energy pump laser to a low-energy signal, as derived from the Maxwell equations [46].

The introduction of chirped pulse amplification, wherein the signal pulse undergoes significant temporal stretching to reduce peak power throughout most of the beamline, offered a huge advancement in the potential to high-power lasers [47]. This was naturally soon combined with OPA as a drive to high-peak powers.

A schematic simplification is given in Figure 2 to show the process of OPCPA.

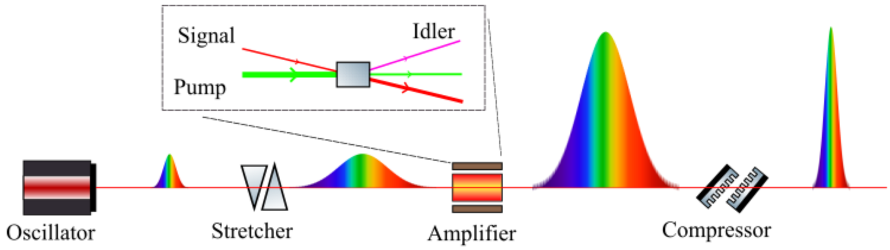

Figure 2. Schematic process of Optical Parametric Chirped Pulse Amplification. The low-power, short pulse is stretched, parametrically amplified, and then compressed to achieve a high-power short pulse. An idler beam is created as a result of the phase-matching in the amplification.

In collinear OPA, the signal and pump beams travel along the same path, allowing for efficient energy transfer. However, this technique faces limitations when it comes to amplifying broadband pulses due to phase-matching constraints, spectral bandwidth limitations, and the spatial walk-off during propagation [48]. In contrast, the extension to noncollinear optical parametric amplification offers a significant advantage for broadband pulses [49]. Non-collinear OPA (NOPA) involves introducing a slight angular mismatch between the signal and pump beams, enabling a broader spectral bandwidth to be amplified. This angular separation allows for a greater range of wavelengths to be phase-matched simultaneously, resulting in a more uniform amplification of broadband pulses. Consequently, the extension to NOPA is a more effective and versatile approach for generating high-energy broadband pulses in ultrafast optics applications. The central wavelength and bandwidth of the amplified pulse depends on the choice of crystal, pump characteristics, and the geometry of the input beams.

Typically, BBO and LBO crystals find common usage in the initial phases of modern high-power laser systems [19,20,24,50,51], primarily due to their excellent optical properties, broad transparency ranges, high damage thresholds, low dispersion, and versatile phase-matching capabilities [52,53]. Both of these crystals facilitate efficient frequency conversion owing to their high effective nonlinearity; BBO is the higher of the two, allowing for shorter crystals, however it suffers a lower laser-induced damage threshold (LIDT) and is not available at larger aperture sizes. Their birefringence aids in compensating for walk-off, and the tunability of amplified frequencies renders them viable across a diverse range of laser sources. The phase-matching of both crystals is temperature-sensitive, with LBObeing more reactive, usually mandating active control [54]. Both crystals offer thermal stability, which is crucial for managing high-intensity laser conditions at a high repetition rate. The ready availability of BBO and LBO offers a sturdy foundation for subsequent amplification stages in complex laser setups.

The main limitation of OPCPA lies in the pumping process; the nature of the pump-to-seed energy transfer effectively restricts the use of only one pump laser at any given stage (though a two-pump technique is possible [55], it has been shown that the interference between the pump lasers in the crystal imprints a temporal modulation on the signal [56]). This requirement mandates a pump laser with substantial energy (in contrast to a Ti:Sapph system, which can depend on multiple lower-energy pump lasers [29]). For this, Nd:Glass laser continues to stand out as the optimal choice for generating the highest energy in laser pulses, primarily due to the accessibility of high-energy flashlamps and the crystal's ease of growth. They are, however, severely limited in repetition-rate, attributed to the substantial thermal load arising from the inefficient absorption of light in the glass from the flashlamps as well as the low thermal conductivity thereafter. A noteworthy advancement in achieving substantial laser energy is demonstrated through the second harmonic generation utilising large-scale DKDP, as exemplified by research conducted at the National Ignition Facility (NIF) [57]. This technique, then, allows for the generation of enormous energy pulses at 527 nm. Acknowledging the advantages of the 527 nm wavelength for OPCPA, we henceforth exclusively use it as the pump source, ensuring the conditions for achieving the highest peak powers in OPCPA processes.

Another constraint of OPCPA is the requirement for the pump duration to match the signal's duration. Consequently, this necessitates a higher power pump in the stretched regime, thereby mandating a larger grating compressor at the end of the beamline. In contrast, Ti:Sapph and Nd:Glass operate as gain media, allowing longer pump pulse durations.

The potential bandwidths in OPA show not only good flexibility in the choice of central wavelengths, but also great breadth (allowing shorter pulse durations) and is indeed the best known method for higher peak power potential. The other likely candidates for high power are strictly limited in bandwidth and can thus only go so far in peak power: the bandwidth of Ti:Sapph, having been the favoured method in high-power laser systems in recent years, does not extend beyond ≃90 nm (≃20 fs) [21,58]; Nd:Glass is achievable at a much larger scale (more energy), but can only reach ≃20 nm (150 fs) [20].

The nature of OPA energy transfer means that there is only very small thermal loading on the crystal caused by absorption of the high-intensity pump [59]. It has been shown that this can be largely counteracted by the careful tuning of the seed angular dispersion and noncollinear angle [60], suggesting minimal limitations to the pulse repetition-rate in OPCPA. Added to this, there is no gain narrowing associated to the amplification. This delegates less stringency on the spectral pulse shaping, allowing for short pulses.

Finally, the temporal contrast is high, owing to the high single pass gain; the pulse duration of the pump beam determines the amplification of the signal [61]. The absence of a pump beam overlapping in time and space provides no amplification to the overall low noise floor and thus yields high temporal contrast in the signal pulses.

Common issues with OPCPA systems include: operating at degeneracy (wherein the idler pulse propagates in the direction of the signal); back-conversion [62,63]; and parasitic second harmonic generation (SHG) [7,9]. A foreseeable bottleneck to OPCPA is the availability of large-aperture crystals. The limits to the crystal sizes for the most common OPA crystals is given in Table 1.

Table 1. Maximum available crystal size, laser intensity damage threshold (LIDT), centre wavelength and maximum bandwidth for the most commonly used OPCPA crystals, considering a 10 ns, 532 nm pump laser.

Crystal	Max Size (mm)	LIDT (GW/cm^2)	λ_0; $\Delta\lambda$ (nm)
BBO	10 × 10	1 [64]	880, 350 [25]
LBO	150 × 150 [24]	2.2 [64]	880; 350 [25]
YCOB	100 × 100 [13]	2.5 [65]	810; 100 [66]
KDP	600 × 600 [67]	0.5 [64]	-
DKDP (70%)	400 × 400 [68]	0.5 [64]	960; 230 [69]
DKDP (95%)	300 × 300 [70]	0.5 [64]	910; 170 [41,71]

To reach higher energies, exceeding the PW regime, it is necessary to increase the aperture size to maintain safe intensities on the final gratings. This suggests the application of either KDP or DKDP as the final gain media; however, based on the best pump laser availability, as discussed, KDP is not viable.

Adjusting the deuteration level in DKDP alters the potential bandwidth and central amplified frequency, as illustrated in Figure 3, this is due to absorption of the idler and phase-matching [41]. This demands careful attention, as achieving an ideal match between the central frequency and the front end is crucial for broadband gain. Additionally, it is desirable to maximise the bandwidth while ensuring homogeneity for optimal performance. One clear challenge with handling such large pulse apertures with such small non-collinear angles is the separation of the idler from the signal following the crystal(s).

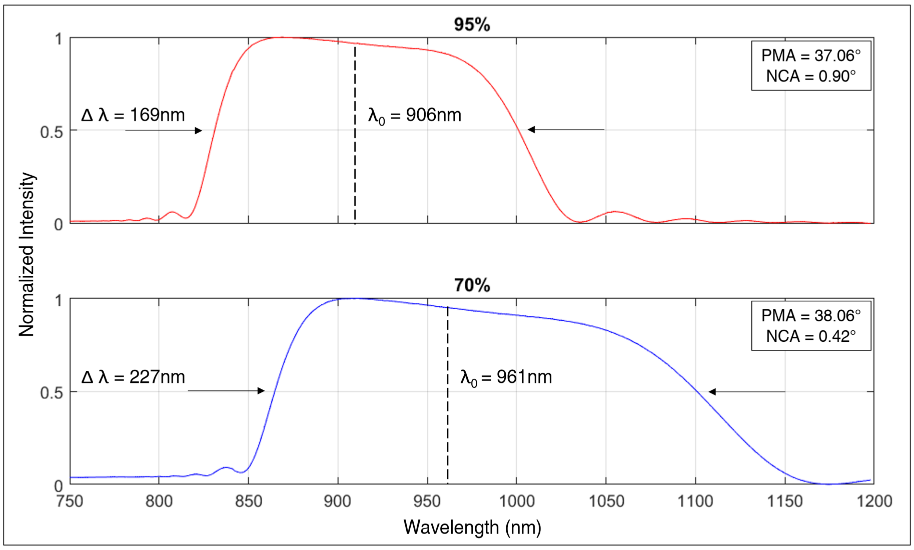

Figure 3. Simulated bandwidth $\Delta\lambda$, central wavelength λ_0, phase matching angle (PMA), and non-collinear angle (NCA) based on DKDP deuteration levels of 95% and 70%, using the Sellmeier equations for DKDP [41].

3. Vulcan OPA History

Figure 4 shows a timeline of the Vulcan laser history with OPCPA, ending at the target date for the new Vulcan 20-20 project completion.

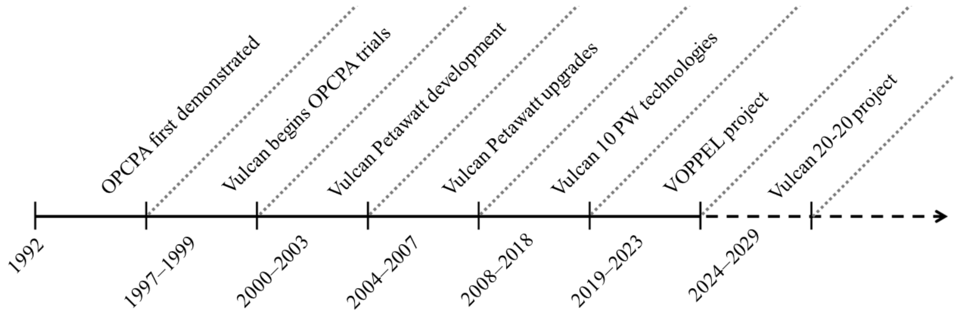

Figure 4. A timeline of the key milestones of OPCPA regarding the Vulcan laser development.

The Vulcan laser at the Rutherford Appleton Laboratory originated as part of the Central Laser Facility's efforts to advance laser technology for scientific research and experimentation. The laser has stood as an experimental tool for users internationally, supporting a wide a diverse range of experiments and studies in the fields of plasma physics, materials science, laboratory astrophysics, and laser-driven particle acceleration. The laser's periodic development and upgrades have been instrumental in keeping Vulcan as a vital tool to the experimental users.

The Vulcan laser began as an Nd:Glass laser in 1976, but has since had a rich history in utilisation of OPCPA technology.

In 1997–1998, Ross et al. already suggested that the benefits of OPCPA show the potential of a 10 PW laser, and began to implement a new front end design for Vulcan, using two BBO amplifiers pumped by Nd:YAG to reach a 1 mJ output with no gain narrowing [72,73]. The second phase of this implementation increased the output power to 500 mJ by using a combination of LBO and KDP as high gain and power amplifier stages, respectively [5].

The formal announcement of the Vulcan Petawatt project took place in April 1999 [74]. The project featured a three-stage OPCPA pre-amplifier utilising a combination of BBO and

LBO, achieving an output of 100 mJ [75]. The results of this implementation were recorded in 2001–2002 [76,77].

In 2005, significant strides were made in enhancing the temporal contrast of both picosecond OPA (psOPA) and nanosecond OPA (nsOPA), underscoring the advantages of OPCPA as previously discussed [78,79]. Subsequent developments in the same year showcased an expanded bandwidth, leading to significantly improved pulse compression [80]. The pursuit of enhanced temporal contrast continued with modifications to the laser front for the Petawatt beamline: a nanosecond front end was introduced in 2007 [81], and a picosecond front end in 2008 [82].

The success of Vulcan Petawatt's front end capability, coupled with the robust pump power from Vulcan Nd:Glass lasers, prompted the conceptualisation of a Vulcan 10 PW upgrade. This envisioned upgrade involved an all-OPCPA system, aiming to achieve 300 J with a 30 fs pulse duration for experiments requiring focused intensity up to 10^{23} W/cm^2 [83–85]. The developmental phase commenced in the late 2000s, focusing on design and experimentation with front end technologies as well as large aperture DKDP amplification. A noteworthy accomplishment during this phase was the demonstration of a broadband OPCPA front end with an impressive bandwidth of 165 nm, achieved using a combination of BBO and LBO in a chirped pump configuration [86]. Another important aspect of the Vulcan 10 PW project involved advancements in high-energy amplification, with OPCPA operations carried out in the formerly designated Target Area East, focusing on the exploration of large-aperture OPCPA [9]. While the building design and laser layout received approval, the project was temporarily halted due to the unavailability of complete project funding. During this period of pause, the facility continued with ongoing developments and testing of OPCPA. This included comprehensive considerations of DKDP [69,87,88], effective management of short pulses [89], and advancements in pulse compression [90].

In recent years, the Vulcan facility has experimented with BBO and LBO amplification as a gain medium in an ultrabroadband front end, which then evolved into an all-OPCPA Petawatt system, known as VOPPEL (Vulcan OPcpa PEtawatt Laser) [25,91]. The extension of this system into the existing TAP beamline commenced in 2021 [92], however the development of the high-energy LBO stages has been paused due to laboratory refurbishment. The architecture and performance of the VOPPEL front end have been subsequently adapted and adopted as a model for the Extreme Photonics Applications Centre (EPAC).

In 2023, the long-anticipated upgrade to the Vulcan system was formally approved, initiating construction of a next-generation laser system. The combination of efficient, stable front end architecture and the large-aperture OPA tests has led to the confidence to meet and exceed the 10 PW prospects initially suggested following Vulcan's first implementation of OPCPA [72]. This new facility, Vulcan 20-20, will increase Vulcan's peak power twentyfold for the user community. The complete system will deliver 20 PW, 20 fs, at a rate of one shot every 5 min.

The design of Vulcan 20-20 is based largely on the Vulcan 10 PW project, with energy and pulse duration pushed to achieve 20 PW, made possible by the advancement of various technologies. These include energy scaling, crystal improvement, high-efficiency broadbandwidth amplification, and better grating availability. The final pulse will reach 400 J at 20 fs (up from 300 J, 30 fs from the Vulcan 10 PW design). The repetition-rate of the system is limited by the pump laser which requires a period for stabilisation as well as capacitor bank recharge following the rapid release of the high required energy. As discussed in the previous section, the OPCPA process is less thermally concerning and could run at a higher repetition-rate, were the pumping capability available.

The front end of Vulcan 20-20 will be similar to the previous work taken on site–particularly the demonstration of a 910 nm seed [86] with improvements to produce 1 J pulses and 150 nm bandwidth. This will then seed the three high-energy, large-aperture OPA stages (developing on the earlier demonstrations [9]). The beam diameters will measure 35 mm and 2 × 200 mm, resulting in a final output of up to 800 J before compression, while preserving the wide bandwidth. To achieve the high OPA gain at such a size, DKDP (doped at 70%, 80% or 95%) is being simulated as the only candidate for the final amplifier crystals. Currently, the decision is split between 95% and 70% deuteration; at 95% the signal bandwidth is further from degeneracy, however at 70% the crystal quality available is much better due to the growth process [68]. The pump laser will operate at 2 × 1 KJ (at 527 nm) in a multi-pass configuration through the Nd:Glass disc amplifiers. Active cooling of the Nd:Glass amplifiers is currently being developed to allow for a repetition-rate of 5 min. Compressibility and specific optical layout are still under consideration, however the required beam size for safe transmission on the large-aperture compressor gratings is expected to be 700 × 700 mm, with a pulse duration of 20 fs. Many challenges are currently being addressed in the design phase for the Vulcan 20-20 project, including idler-beam separation, suitable crystal lengths and quality, sufficient amplifier cooling, and shot-to-shot consistency on target. The laser system's overall reliability and durability will be directed towards upholding Vulcan's reputation as a dependable international user facility for many years to come.

4. Conclusions

Development of OPCPA has improved regularly since its inception. The possibility of large-aperture crystals and broadband flexibility presents it as the only viable option for the next generation of high-peak-power lasers, reaching the 10s and 100s of Petawatts. Various facilities are experimenting and driving towards these targets, utilising DKDP as the large-aperture amplification medium, pumped by frequency-doubled glass lasers at 527 nm. The experience at the CLF on the Vulcan laser has led to the initiation of a recently approved Vulcan 20-20 project, to delivery 20 PW pulses to target areas as a new experimental facility. The laser will be amplified entirely by OPCPA and aims to be operational in 2029.

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