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14. ABSTRACT

Over the last decade Optical Parametric Chirped Pulse Amplification (OPCPA) has matured significantly, and many new laser systems are exploiting the advantages of ultra-broad bandwidth amplification, high gain, wavelength flexibility, reduced thermal effects, and increased temporal contrast, compared to traditional Chirped Pulse Amplification (CPA). The scalability of OPCPA is limited mostly by the available picosecond duration pump sources, since shorter pump pulses are required for broadband Optical Parametric Amplification (OPA). The incorporation of Divided Pulse Amplification and coherent pulse combination will allow a >250% increase in pump

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Report Title

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Over the last decade Optical Parametric Chirped Pulse Amplification (OPCPA) has matured significantly, and many new laser systems are exploiting the advantages of ultra-broad bandwidth amplification, high gain, wavelength flexibility, reduced thermal effects, and increased temporal contrast, compared to traditional Chirped Pulse Amplification (CPA). The scalability of OPCPA is limited mostly by the available picosecond duration pump sources, since shorter pump pulses are required for broadband Optical Parametric Amplification (OPA). The incorporation of Divided Pulse Amplification and coherent pulse combination will allow a >250% increase in pump pulse energy compared to the previously proposed design. OPCPA with this high energy pump will allow the PhaSTHEUS facility to reach record peak powers from a quasi-single cycle pulse system. Relativistic intensities at this level enable interesting plasma physics such as high-order harmonic generation from solid targets and proton acceleration

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Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Benjamin Webb	0.00	
Nathan Bodnar	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Lawrence Shah	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Ahmad Azim	0.00	Optics
FTE Equivalent:	**0.00**	
Total Number:	**1**	

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

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FTE Equivalent:	
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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Defense University Research Instrumentation Program (DURIP)

Army Research Office (ARO) DURIP AWARD (Agency Contract Number W911NF1210484)

Phase-Stabilized Terawatt High Energy Ultra-Short (PhaSTHEUS) Laser Facility

Period covered by report: 8/25/12-8/24/14

Final Report

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ABSTRACT

Over the last decade Optical Parametric Chirped Pulse Amplification (OPCPA) has matured significantly, and many new laser systems are exploiting the advantages of ultra-broad bandwidth amplification, high gain, wavelength flexibility, reduced thermal effects, and increased temporal contrast, compared to traditional Chirped Pulse Amplification (CPA). The scalability of OPCPA is limited mostly by the available picosecond duration pump sources, since shorter pump pulses are required for broadband Optical Parametric Amplification (OPA). The incorporation of Divided Pulse Amplification and coherent pulse combination will allow a >250% increase in pump pulse energy compared to the previously proposed design. OPCPA with this high energy pump will allow the PhaSTHEUS facility to reach record peak powers from a quasi-single cycle pulse system. Relativistic intensities at this level enable interesting plasma physics such as high-order harmonic generation from solid targets and proton acceleration

Keywords: Ultrashort laser; single cycle pulse generation; OPCPA

Original Document September 2011

Defense University Research Instrumentation Program (DURIP)
DURIP AWARD

Phase-Stabilized Terawatt High Energy Ultra-Short (PhaSTHEUS) Laser Facility

Final Report

1. Introduction:

This funding enabled the purchase of critical equipment for the construction of a new high energy OPCPA facility, PhaSTHEUS. Initially this facility was designed to reach a peak power of 20 TW with phase controlled quasi-single cycle pulses [1]. However, during the course of this project advances in Divided Pulse Amplification (DPA) [2], [3] and coherent pulse combination [4], [5] have lead to the re-design of the OPCPA pump laser which will enable an increase in the OPCPA peak power output to >50 TW. Quasi-single cycle pulses at this power level will produce relativistic intensities high enough for the generation of high-order harmonics (HHG) from a solid target via a relativistic oscillating mirror [6] or Coherent Wake Emission (CWE) [7]. These advances are expected to produce record-breaking high brightness attosecond (10^{-18} s) or even zeptosecond (10^{-21} s) pulses in the near future.

2. Budget:

The reinterpretation of the original design lead to several changes in the budget, as the equipment required for pulse splitting in DPA and parallel amplification chains for coherent pulse combination were not originally included. The original budget and the final purchase details are summarized in Table 1. The projected cost was $302,800, and the full amount awarded by the DURIP has been spent.

Table 1: Purchasing

Proposed Equipment	Projected Cost	Final Specs	Final Cost	Vendor
Broadband jitter-free acousto-optic modulated stretcher	$114,510	HR45 broadband Dazzler and HR800 jitter-free Dazzler	$144,516	Fastlite
Pockels Cells	$8,100	Two Pockels cells for isolation of each amplifier channel	$13,360	Quantum Technology
		Faraday Isolator	$2,210	EOT
Flashlamp Pumped Amplifiers	$137,700	Four flashlamp pumped 19 mm diameter Nd:YAG amplifiers	$139,667	Continuum Lasers
		Nd:YAG crystals	$3,047	VLOC, Inc.

Nonlinear crystals	$38,140	Not purchased	$0	N/A
Glass Compressor	$4,350	Not Purchased	$0	N/A
Total	**$302,800**		**$302,800**	

3. Description of Equipment:

The following provides greater detail on the equipment purchased as well as further details explaining the modifications from the original budget.

a. *Broadband Stretcher (Dazzler system)*

A broadband jitter-free acousto-optic programmable dispersive stretcher (Dazzler) was purchased for $114,516 however it was determined an additional smaller Dazzler was also required for improved control for an additional cost of $30,000. An extra 20 W RF amplifier was purchased to provide greater pulse contrast by seeding the optical parametric amplifiers (OPAs) with higher energy. The Dazzler stretcher system will provide expert control of the spectral phase across the entire spectrum of 550 nm to 1050 nm. This ultra-broad spectrum will be amplified by “two-color” OPA pumping which will provide gain across the entire spectrum and produce high energy 5 fs duration pulses.

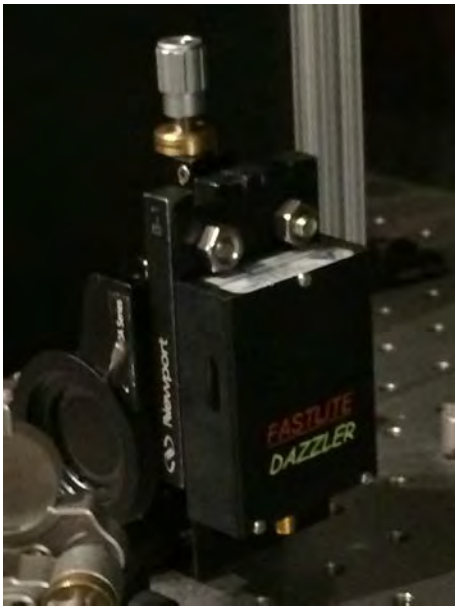

Figure 1: Broad bandwidth Dazzler

b. *Pockels cell*

The original budget included a single Pockels cell ($8,100) to isolate the oscillator from the amplifier chain. Due to the increase in the number of amplifiers, specifically the introduction of parallel high energy amplifier chains, two Pockels cell were purchased for $13,360. An additional Faraday isolator was also necessary, and purchased for $2,210.

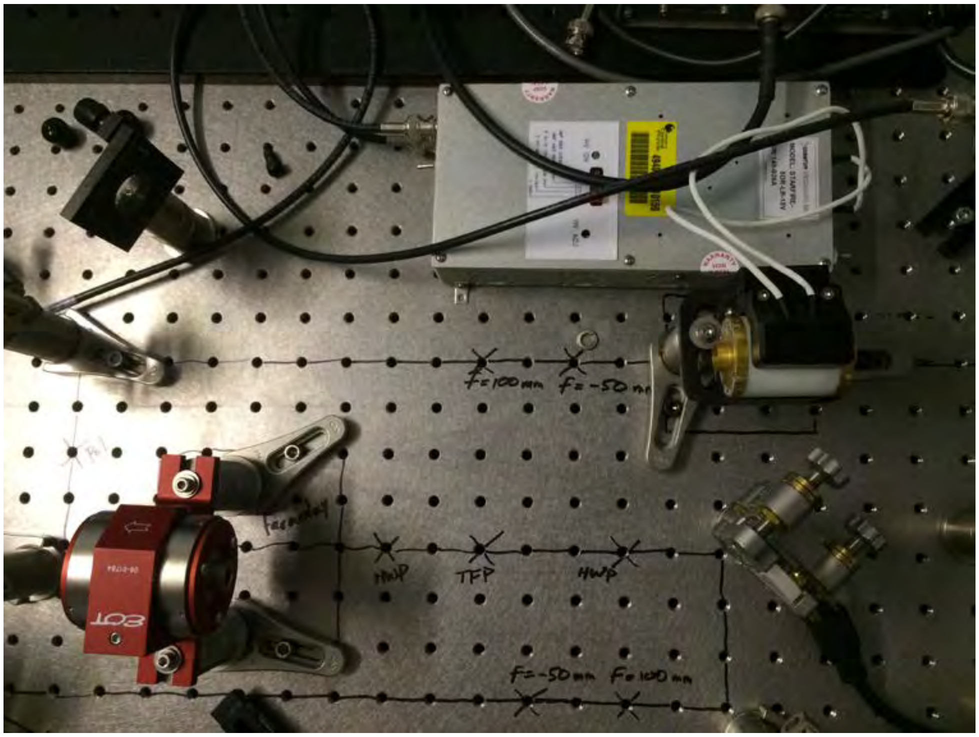

Figure 2: One Pockels cell and driver (upper right) along with the Faraday isolator (lower left)

c. Flashlamp pumped amplifiers

The original DURIP proposal budget included two flashlamp pumped amplifiers for 18 mm diameter Nd:YAG rods and a single flashlamp pumped for a 25 mm diameter amplifier rod for a total budget of $137,700. Upon further review, it was realized that the 25 mm diameter amplifier would cause significant beam quality degradation and therefore was not a viable option for this application. As such, the original design would have been limited to ~1 Joule of output energy based on the damage threshold of the originally proposed 18 mm diameter amplifiers. In order to overcome this limitation, we found that DPA could enable us to extract >3 Joules by creating two parallel amplifier chains with a pair of amplifiers in each channel. For this, four flashlamp pumped amplifiers for 19 mm diameter Nd:YAG rods were purchased from Continuum Lasers for $155,700 based on their superior amplifier head design and higher stored energy. Additionally, two 7 mm diameter Nd:YAG rods were purchased for $3,047 to be placed into existing amplifiers for pre-amplification after splitting the original pulse into four replicas.

The implementation of DPA and coherent pulse amplification is described in greater detail in the next section of this report “**New design for OPCPA pump**.”

Figure 3: Two of the power supplies for the 19 mm diameter amplifiers

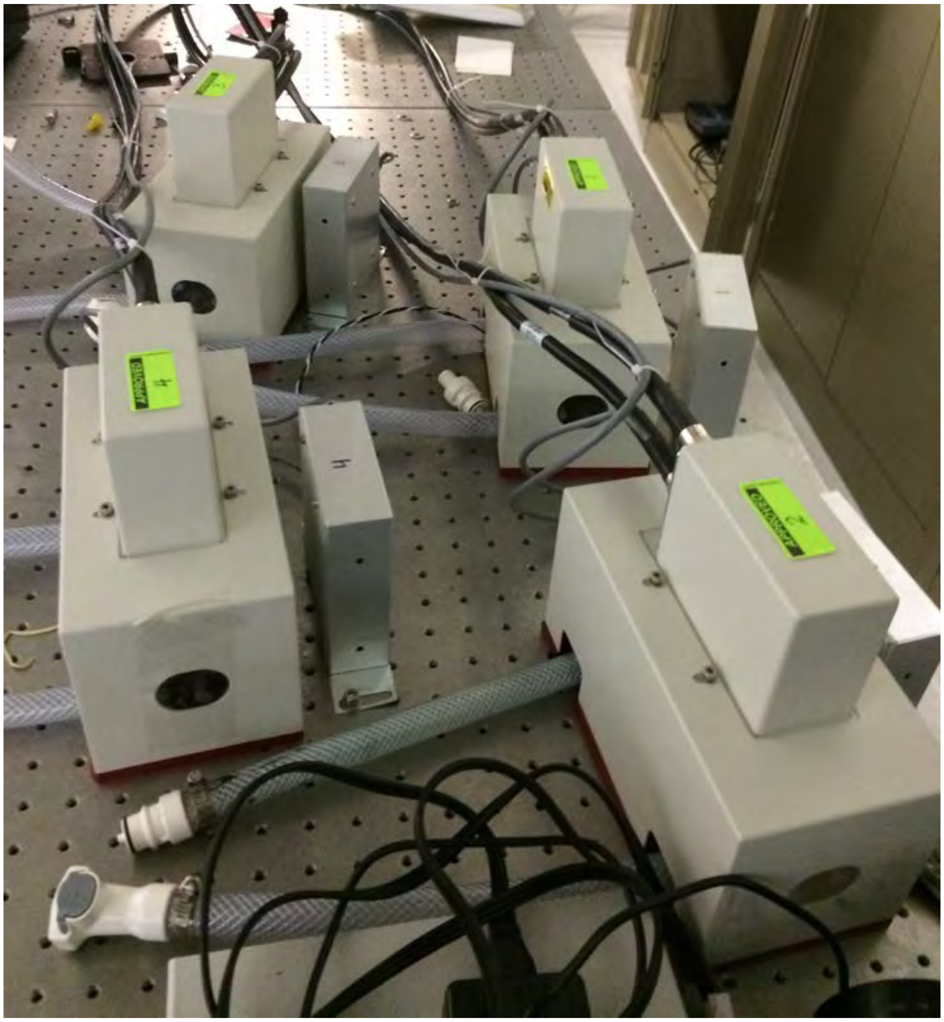

Figure 4: The amplifier heads for the 19 mm diameter amplifiers

d.Nonlinear crystals

In order to pump the OPAs with two colors (532 nm and 355 nm), large aperture LBO crystals ($29,200) are required to generate the 2nd and 3rd harmonics of the 1064 nm Nd:YAG high energy pump laser. The cost of these crystals increases quickly with aperture size, and the necessary crystal size depends on the coherent pulse combination efficiency of the new pump design. The combination efficiency of this cutting-edge technique has not been well established for solid state lasers. Therefore, the purchase of the large LBO crystals has been delayed until the high energy pulse combination has been completed. The cost of this additional equipment will be covered as part of ongoing research efforts.

The purchase of the BBO crystals ($8,940), to be used as non-collinear optical parametric amplifiers (NOPAs), has been delayed for the same reason as the LBO crystals.

e. *Glass Compressor*

A compressor made of highly dispersive SF57 glass ($4,350) was to be used along with chirped mirrors to compress the OPCPA output to 5 fs at the end of the system. However Schott has discontinued stock of this type of glass, and making a custom melt would not be cost effective. We are currently re-designing the dispersion management to use a different type of glass compressor; therefore, no purchase has yet been made.

4. New design for OPCPA pump:

The implementation of DPA allows “stretching” of the pulse duration in order to reach twice the saturation fluence without being limited by nonlinear effects or optical damage without using spectral dispersion as in chirped pulse amplification. The proposed OPCPA pump duration of 100 ps necessitates that the peak irradiance be lowered by a factor of ~8 to maximize energy extraction in our amplifiers. Therefore, the pump design has been modified to amplify and coherently combine 8 pulses, to a single pulse with ~5 Joules (Figure 5). The oscillator and subsequent fiber amplifier provides a ~50 nJ, seed for a lamp-pumped regenerative amplifier running at 5 Hz. A volume Bragg grating (VBG) placed in one end of the cavity narrows the bandwidth to ~10 pm yielding a 100 ps transform-limited pulse with 3 mJ upon ejection from the regenerative amplifier. Two pulse-splitting stages produce a train of 4 pulses which are amplified to ~25 mJ by two inline 7 mm diameter amplifiers. These 4 pulses are then split into 8 pulses, which are divided between 2 identical amplifier channels each consisting of a double-pass 10 mm diameter amplifier and two inline 19 mm amplifiers. The 10 mm diameter amps boost the total energy for pulses in both channels to ~900 mJ, and the final amplifier stage yields ~8 J. When all 8 pulses are coherently combined to a single pulse, we anticipate the preserved energy at 1064 nm will be 5 J. Second and third harmonic generation stages would then generate 1.7 J of 532 nm and 0.9 J of 355 nm for pumping multiple OPA stages. This system utilizes pre-existing equipment; except for the new 19 mm diameter amplifiers which were chosen for their high gain and stored energy which is required for the large jump in energy from the output of the 10 mm amplifiers.

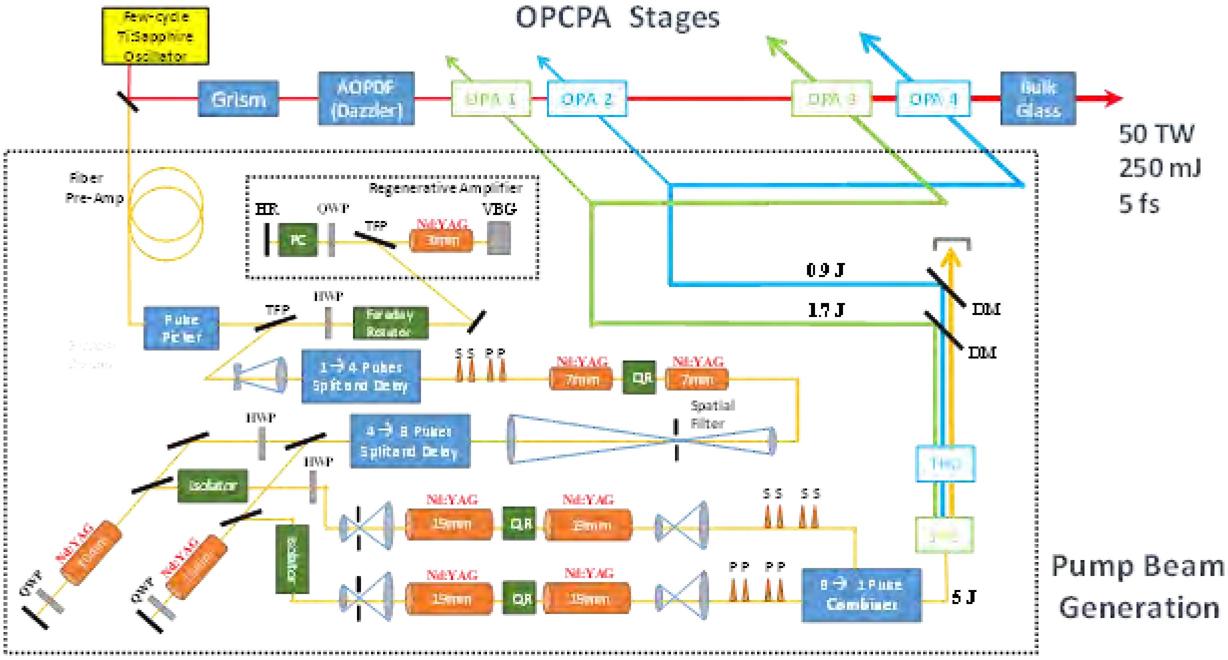

Figure 5: New pump design utilizing DPA and coherent combination of 8 replicas each with 100 ps pulse duration.

The pulse division, amplification and coherent combination have been carefully simulated using an array of Jones matrices to represent the polarization as well as the phase and energy of each temporally multiplexed pulse. This polarization and phase information is carried through the amplification stages along with the addition of nonlinear phase (B-integral) in order to accurately model the effects of gain saturation and nonlinear effects for our active DPA design. It would be overly complicated to map nonlinear phase across full 2D beam profiles, so only the peak B-integral of each pulse in the train is calculated. In the model, dispersion losses are ignored since the bandwidth is narrow, and spatial losses are neglected as well since we assume identical amplifiers and perfect beam profiles. The code calculates the combining efficiency and generates several plots showing how gain saturation affects the energy distribution across the pulse train, and gives information about the total energy and maximum B-integral of the pulse train (Figure 6). Note how the pulse trains in the two plots below are mirrored because the first pulse enters the 19 mm amplifier as the least energetic and exits as the most energetic (Figure 6b), this balance of gain saturation across the pulse train results in the minimization of the difference in B-integral between all the pulses since the majority of the B-integral phase is acquired in the final amplifier.

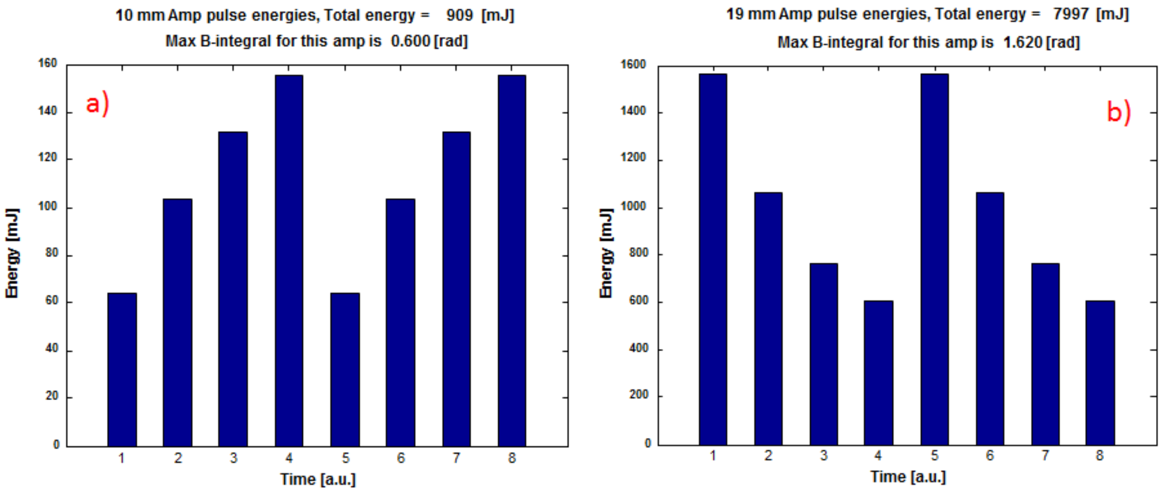

Figure 6: These two plots show the amplification in the final two amplifiers, where each set of 4 pulses in the a) 10 mm amplifier and b) 19 mm amplifier plots are actually contained in the same diameter amplifier, but spatially isolated in a second parallel channel (Figure 5).

Additionally, the simulation provides optimal the half waveplate orientations in each splitting stage for either minimum B-integral phase variation across the output pulse train or minimum pulse energy difference (Figure 7), afterward the half waveplates in the combiner stages are optimized for best polarization combination after a polarizer. It was determined that optimizing for B-integral difference gives ~40% more combined energy compared to optimizing for energy difference. In practice it would be extremely difficult to detect the phase difference across the pulse train, but this model serves as a guide for obtaining the appropriate output pulse train shape for minimum B-integral difference (Figure 7a).

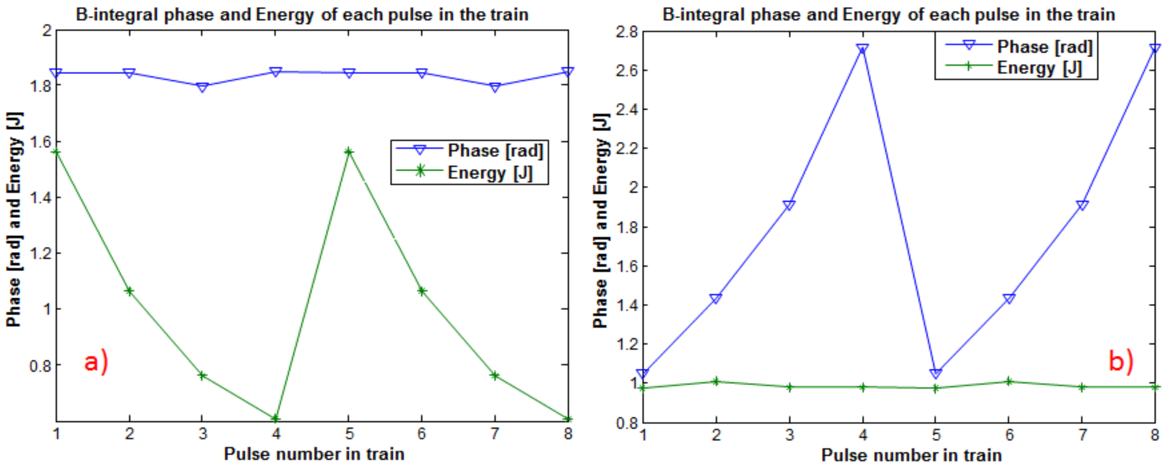

Figure 7: a) In this plot B-integral phase difference across the pulse train has been minimized, where the pulse energy is not. b) When the simulation is told to minimize the difference in pulse energy across the pulse train the resulting differences in B-integral are severe, and cause a poor combination efficiency of < 40%.

The division/recombination elements can be implemented in multiple geometries. When modeling each of the elements with Jones matrices, it was discovered that the phase/polarization coding across the delayed pulse train of some of the splitting and combining elements do not match and therefore different division/recombination elements cannot be arbitrarily paired together.

The DPA simulation code was written to be modular, where division/recombination elements (type and delay structure), amplifier geometries (i.e. double-pass, single-pass, 1 channel, or 2 channel), and many other properties could be quickly enabled or disabled. This allowed for testing of many different permutations of all the amplifiers and possible DPA architectures. Since the degrees of freedom necessary for compensation of gain saturation increase dramatically for delayed pulse trains with >4 pulses, The design options were limited to a maximum of 4 DPA pulses per channel, which required at least 2 channels of amplifiers to reach our goal of ~8 times decreased peak power. The simulation results helped narrow the rest of the options down to the top three architectures in terms of performance, and final design (Figure 1) was chosen by which option would be simplest and most robust in terms of implementation. For this particular design, manual adjustment of the pumps voltages of each amplifier revealed that the lowest cumulative B-integral phases can be achieved by decreasing the pump voltage of the 7 mm amps to 70% and then running the 10 mm and 19 mm amplifiers at full pump voltage. Quarter waveplates will also be installed before and after each of the amplifiers in order to decrease the B-integral by a factor of 2/3 for circularly polarized pulses compared to linear polarization [8].

5. Status of PhaSTHEUS OPCPA facility:

All necessary components for the pump generation except for the large aperture pulse combination and harmonic generation optics have been received. Amplification in the Nd:YAG pump line up to 160 mJ has been demonstrated for a single pulse. Currently, experiments are being conducted to determine the combination efficiency of DPA with our flashlamp pumped free-space amplifiers. The high energy coherent pulse combination and subsequent generation of 2nd and 3rd harmonics of 1064 nm for pumping the OPA stages will be completed by Spring 2015. After completion of the OPCPA pump, broadband optical parametric amplification to 280 mJ will commence, followed by pulse compression of 250 mJ pulses to 5 fs.

Dr. Lawrence Shah, Research Assistant Professor of Optics leading the Laser Development team inside the Laser & Plasma Laboratory of the Townes Laser Institute, has provided technical management for this program along with Michael Chini, Senior Research Scientist. The design and construction of the facility have involved several students, and contributed to their education:

- Benjamin Webb (PhD student): is the lead student on the project. Design of the system, procurement, and implementation of the pump laser as the focus of his PhD research.
- Nathan Bodnar (PhD student): is the lead student on high repetition rate OPCPA, and has been supporting this project as part of his PhD research.
- Ahmad Azim (undergraduate student): has been working with Ben Webb as an introduction to working in a laser research laboratory.

6. References:

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