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CY2019 SUMMARY FOR Z-PETAWATT LASER ACTIVITIES

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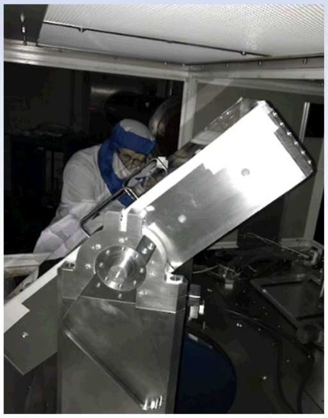
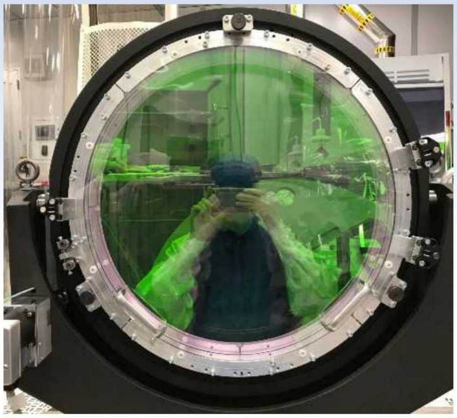


SAND2020-XXXX

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CY2019 SUMMARY FOR ZPW ACTIVITIES

EXECUTIVE SUMMARY:

The high-energy upgrade of the Z-Petawatt (ZPW) laser system involved a shot hiatus starting in October 2018 to allow the installation of full-aperture optics in the chain, including in the main amplifier section as well as in the branches associated with the ZPW compressor and co-injection (the narrowband nanosecond operating mode that is co-bored with Z-Beamlet).

Laser shots resumed May 1st, with most shots since being in the ns mode to reduce complexity (while conditioning optics and calibrating diagnostics) as well as to support experimental requests. To facilitate experimental needs while a final full-sized co-injection optic was prepared, a sub-apertured beam has been used for experimental applications and a full-apertured beam has been used to validate the system. In the latter case, the beam is directed to a large calorimeter placed before branching occurs to the ZPW compressor or co-injection. As of September 2019, full-aperture co-injection shots had ramped up to 960J in 2.3ns, with many cross-calibrations being used to map out a relative humidity dependency in the leaky diagnostic mirror. Several such cross-calibration shots have been done using a chirped pulse seed as well, verifying that the diagnostic calibrations are valid in both broadband and narrow-band modes. Summarizing, since May 1st of 2019 when shots resumed, 93 full system shots were performed with the ZPW laser. This included 2 co-injection shots with ZBL into Z (in support of MagLIF), 26 Pecos gas cell shots (in support of MagLIF), 11 Conchas gas cell shots (in support of UXI applications development), 6 Jemez shots (in support of backlighter development), and 48 calorimeter shots (in support of validating the system performance). Of these 93 shots, 45 shots were in conjunction with ZBL.

As work shifted to the ZPW compressor in the mid-Summer, the Chama target chamber's lens-based focusing elements (consisting of an f=2m lens and a 60cm diameter mirror) were removed from the vacuum system. Upon inspection, both optics were noted to have an oily film on them. As such, there is now a heightened sensitivity to contamination of the new ZPW compressor multi-layer dielectric gratings (which cannot be cleaned on site). ZPW efforts then shifted to other areas while developing a plan to address such concerns.

Contrast enhancement is one such area, with high temporal contrast being necessary for optimally controlled target interactions such as high efficiency x-ray, neutron, or proton generation. The final plan is to use the nonlinear nature of a picosecond optical parametric amplifier (ps-OPA) to improve the contrast of the seed pulse for the ZPW front-end. To this end, we built and tested the ps-OPA with a compressed pickoff from the ZPW seed laser, which demonstrated 2-3 orders of magnitude improvement in the contrast compared to the situation without the ps-OPA. In fact, this pushed the detection limit for the Sequoia autocorrelator diagnostic, motivating the use of a higher dynamic range Tundra autocorrelator.

With the contamination plan taking shape, additional ZPW work has gone on in parallel, including: The alignment of the input telescope to the ZPW compressor; The mounting of beam dump glass in newly constructed frames to catch specular grating reflections; the mounting of the Chama off-axis parabola in its bezel and mount; early work with the ZPW compressor gratings; and preparatory work on the ZPW FOA.

DETAILS:

THE UPGRADE:

The ZPW full-aperture upgrade was designed to increase the beam aperture of the laser and thus to increase the energy. The effort was centered around adding a minimum number of full-aperture optics (>60cm diagonal) while utilizing existing full-aperture infrastructure (such as the main amplifiers and the plasma electrode Pockels cell). While aspects of the work had been going on for several years, the effort began ramping up in 2018, culminating in a dedicated system shutdown for the upgrade in October of 2018. Operations resumed on May 1st of 2019. Including all requirements for the petawatt (chirped pulse amplification) and co-injection modes of operation through the Phase C Target Bay, the effort required 22 full-aperture optics and mounts plus the 10 large main amplifier slabs. 31 optical surfaces were required to be coated (of which all but 4 surfaces were coated at Sandia). The effort needed 31 new or modified axes of motion control.

SYSTEM PERFORMANCE AT COMMISSIONING:

BEAM QUALITY:

Upon re-activation of the system, initial user applications involved using the sub-aperture co-injection pulse for MagLIF applications. Knowing this need, the last full aperture mirror installation specifically needed for co-injection has been delayed until the winter shut down of 2019. As such, some cross-calibrations and all experimental co-injection shots have been done in this sub-aperture narrowband mode. Note that changes in the apodization and magnification have led to the sub-aperture beam being 16% larger in diameter than before the upgrade (or 36% larger in area). Full-aperture shots have also been performed, with the beam being slightly reduced from the design point of 27.0cm X 31.7cm (A=856cm^2) to 25.9cm X 29.1cm (A=754cm^2), which is a 12% reduction in area due to some minor clipping issues. Near field peak-to-average levels are currently about 2.4:1 but can reduced through the use of a spatial light modulator system which is installed but still in development. Using only a single actuator focus corrector on shot, Strehl ratios are in the 0.55 to 0.65 range (as analyzed with a circle inscribed in the beam area to maintain Zernike decomposition analysis).

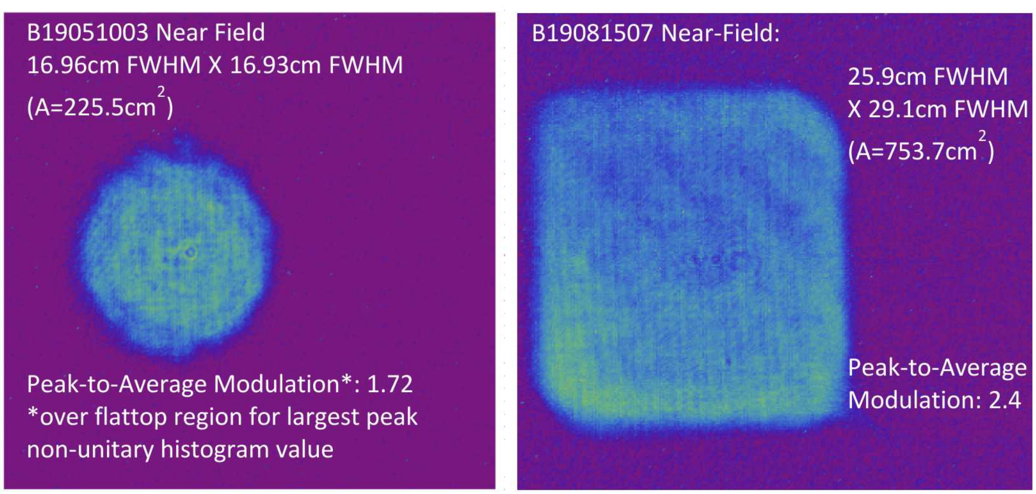


Figure 1. Near-field beam profiles for the (left) sub-aperture and (right) full-aperture ZPW system.

ENERGETICS AND CALIBRATIONS:

For high energy cross-calibration shots, the beam is directed to a large calorimeter placed before branching occurs to the ZPW compressor or co-injection. In the narrowband co-injection mode, testing has demonstrated kJ-level operation and follows a 2-pass saturated gain model quite well. We believe that limitations in the damage threshold of the vacuum spatial filter injection mirror and the AR coatings of the 64mm diameter rod will limit the injected energy to about 45J, allowing 2.3kJ in concept at narrowband 1054nm (per the saturated gain model). SNLO modelling indicates that this beam at 2.3ns could generate 1.59kJ at 527nm for ZBL-like applications. Operating envelope details and the functional parameters are in the process of being studied.

A few shots have been performed in the broadband CPA mode, with the gain being slightly lower due to gain-narrowing. Over 300J has been demonstrated at full-aperture with the chirped seed. The second broadband shot used OPCPA pulseshaping to generate a spectral dip in the seed pulse capable of partially addressing gain narrowing. Although the gain was slightly lower, this generated an amplified chirped pulse of 1.70ns average width versus 0.95ns for the previous shot when a flattop seed pulseshape was used. At 4.0nm/ns chirp, the spectrum was increased from 3.80nm to 6.80nm using the shaped pulse approach, corresponding to a 78% increase in amplified bandwidth and chirped pulsewidth. This facilitates both shorter compressed pulses while mitigating B-integral effects in the chirped domain of the main amplifiers. Note that the current beamsize (with a 1.8x safety derating for beam modulation) allows for 420J operation at 600fs or 1.25kJ at 10ps, per the vendor tested laser-induced damage thresholds (LIDTs). It should also be mentioned that the LIDTs vary slowly around 600fs so shorter pulsewidths in the 400 to 600fs would have similar limits.

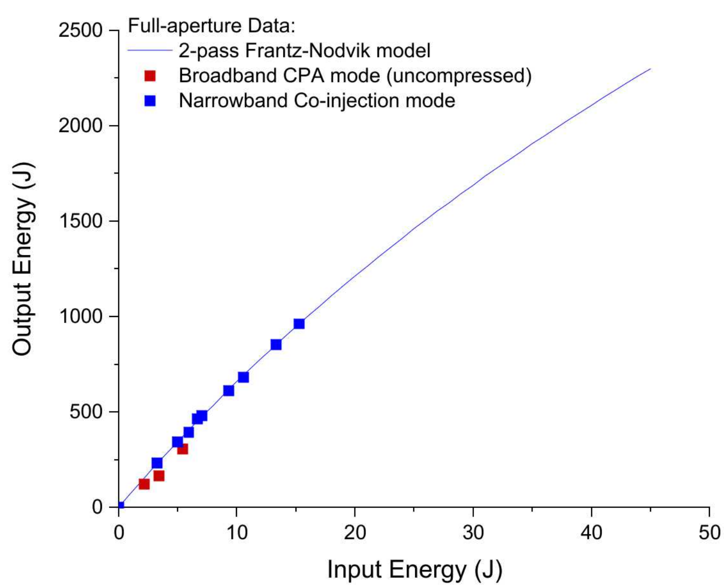


Figure 2. Measured and modelled energy performance for full-aperture ZPW system.

The relative humidity (RH) in the Laser Hi-Bay routinely runs 5 to 20% but can ramp up to about 45% during high humidity times like the summer monsoon season. As water molecules begin to adhere to the coating of the leaky mirror used for diagnostics, the transmission is affected subtly, causing the calibration of the energy to vary by up to 15%. As the system ramped back up, the RH dependency was tracked during various cross-calibrations in different operational modes. The dependency has been consistent regardless of aperture size or bandwidth. As such, a fit to the dependency allows us to maintain energy measurements to within the 2-3% accuracy of the calorimeter.

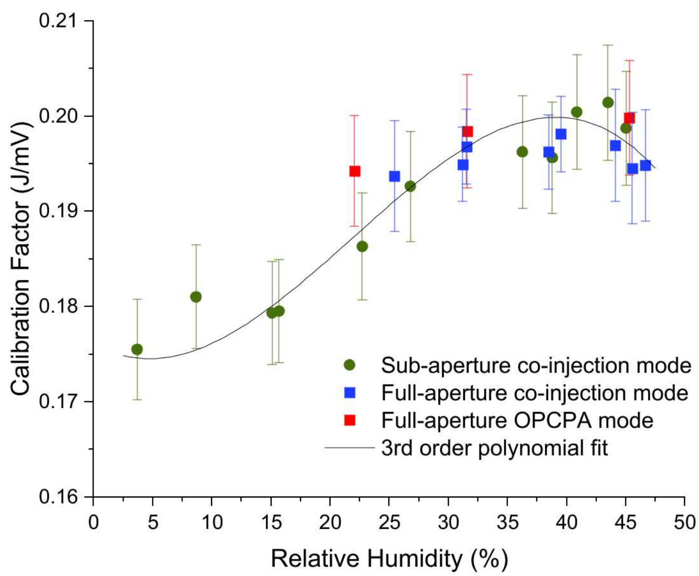


Figure 3. Relative humidity dependence of energy diagnostics calibration for the ZPW system.

SHOT STATISTICS FOR CY2019:

Since May 1st of 2019 when full operations resumed, 93 full system shots were performed with the ZPW laser. This included 2 co-injection shots with ZBL (in support of MagLIF), 26 Pecos gas cell shots (in support of MagLIF), 11 Conchas gas cell shots (in support of UXI applications development), 6 Jemez shots (in support of backlighter development), and 48 calorimeter shots (in support of validating the system performance). Of these 93 shots, 45 shots were in conjunction with ZBL. These overall numbers are similar to previous years (see Table 1), especially when considering the upgrade downtime.

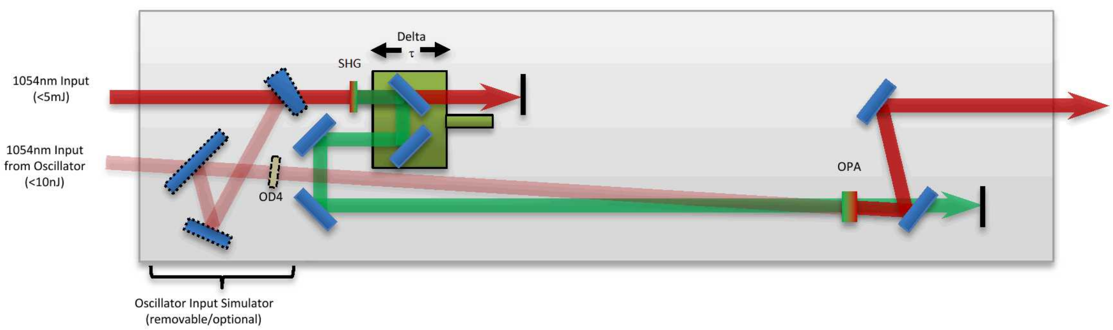
Year	Total ZPW Shots	Shots with ZBL	Shots into Z	Downtime	Comments
CY2017	74	28	5		Co-injection method developed and Chama chamber activated
CY2018	122	68	8	3 months	Full-aperture upgrade begins
CY2019	93	45	2	4 months	Full-aperture upgrade ended

Table 1. Annual shot data comparison ZPW system.

CONTRAST ENHANCEMENT:

In the world of high intensity lasers, high contrast pulses are needed for optimal control of laser matter interactions. For intensities at 10^{21} W/cm^2, a contrast of 10^{-8} means that a pre-pulse will be at the 10^{13} W/cm^2, which can generate undesired plasma that negatively impacts laser matter interactions. ZPW has historically been able to perform at this 10^{-8} level without additional measures but modern experiments (such as efficient x-ray or neutron generation) demand even higher performance. Regarding our approach to additional contrast enhancement measures, the plan is to use a diode-pumped Nd:Phosphate glass regenerative amplifier (using chirped volume Bragg gratings or CVBG before and after for chirped pulse amplification) to provide the pump pulse for a picosecond optical parametric amplifier (ps-OPA). The contrast improved pulse from this will then inject into the ZPW front-end before the OPCPA section.

The regen portion (using an APG-1 Nd:Phosphate glass amplifier head from Cutting Edge Optronics) was tested in January 2019 with a narrowband ns seed. Operation with this seed was shown at 12mJ with <1.5 % RMS (which is a good performance) but there have been problems seeding it with a broadband chirped source. To be clear, a photonic crystal fiber (PCF) section was used to spectrally broaden the output of an 800nm Ti:Sapphire oscillator such that a section at 1054nm could be used. While the time-integrated spectrum looked smooth in the region of interest, the pulse that was chirped by the CVBG looked unstable temporally with a fast photodiode on a shot-to-shot basis. The root cause is that the PCF actually generates deeply varying spectrum for each pulse at 80MHz which average to a smooth stable spectrum on a standard spectrometer.



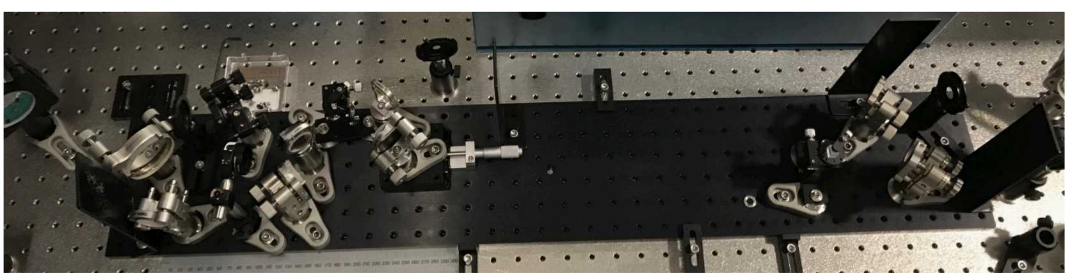


Figure 4. Layout (top) and photo (bottom) of the ps-OPA for contrast enhancement.

While a fix is developed for the broadband seed at 1054nm, we decided to build and test the ps-OPA portion with a compressed OPCPA section pickoff (see Figure 4). The input to the ps-OPA was <5mJ at 1054nm at 500fs from the Damage Tester. In this test, the 1054nm then splits into an OPA seed pulse and a second harmonic pump pulse. The seed at 1054nm is a 4% wedge reflection of the input beam followed by an OD4 filter, taking the seed level to the 10nJ level (in order to be close to what we expect with the eventual case for the broadband oscillator seed). The rest of the 1054nm light was used for SHG in a

3.5mm long LBO crystal, resulting in ~2mJ level 527nm light. The SHG then pumped the seed in an OPA crystal (7mm long LBO). A beam crossing angle of 1-2degrees in the OPA crystal was used due to both spatial constraints in this breadboarded set-up and due to the need to angularly separate the idler pulse. A delay line was used on the pump pulse to allow temporal overlap to within the 500fs pulsewidth (corresponding to 75micron in the double-pass delay line). The resulting signal output at 1054nm was at the 10-100mJ level. Beam dumps are used behind the dichroics after the SHG and OPA to eliminate unwanted light. The setup is breadboarded for quick installation after the diode-pumped regen works in CPA mode.

Note that, when applied with a broadband oscillator seed in the final configuration, the dashed optics in Figure 4 (the wedge, the two fold mirrors, and the ND filter) will be removed and the oscillator seed input time adjusted to facilitate temporal overlap in the OPA.

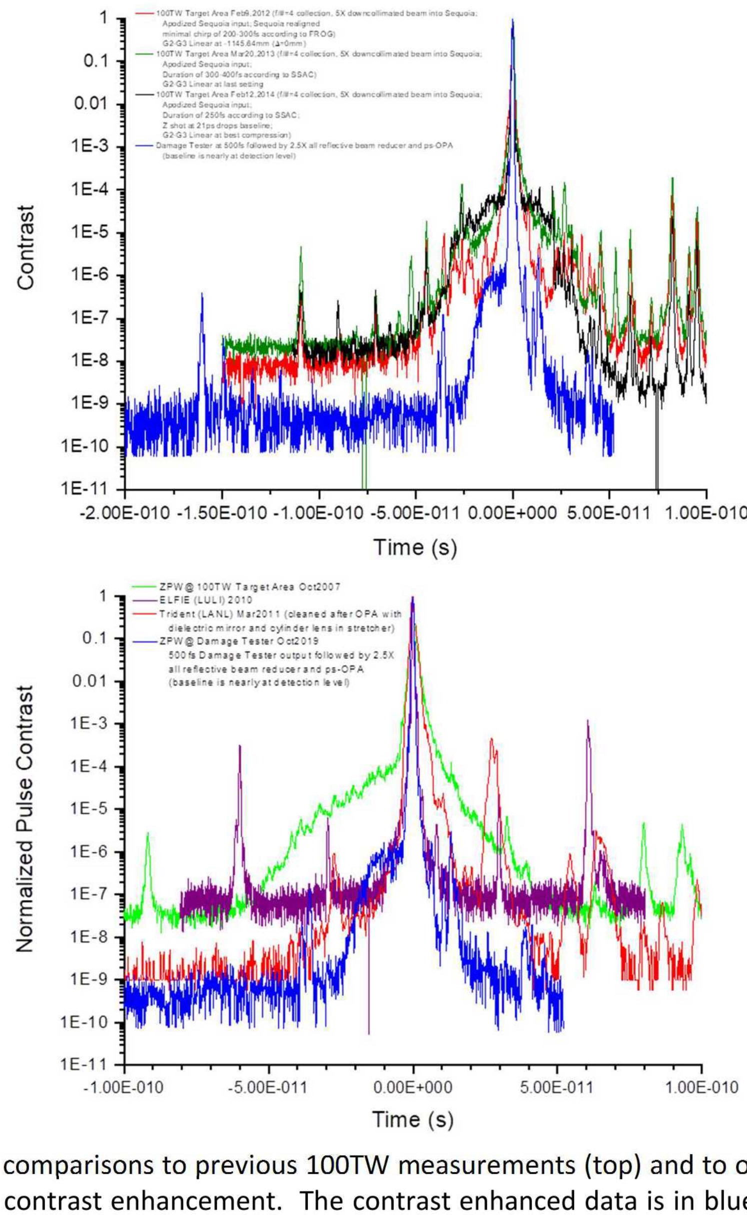


Figure 5. Contrast comparisons to previous 100TW measurements (top) and to other facilities (bottom) for the ps-OPA for contrast enhancement. The contrast enhanced data is in blue. Note that the other facility data is older and that more recent data from world-class facilities tends to be 1-2 orders better, with several facilities since 2015 reporting 10^{-11} levels at -100ps.

The performance of the ps-OPA was measured with a 2007 model Sequoia autocorrelator. A baseline trace at the Damage Tester (no ps-OPA) was taken, showing a contrast that was 10^{-5} at -25ps delay and 10^{-7} at <-50ps. With the ps-OPA, the cleaned Damage Tester pulse (in blue on the Figure 5) is better than previous scans at the 100TW Target Area (top in Figure 5) and compares favorably to other facilities (bottom in Figure 5). Contrast improved to 10^{-9} at -25ps delay and $5x10^{-10}$ at <-50ps. The baseline sensitivity of the older Sequoia is around 10^{-10}, which is why the performance will be cross-checked with a recently purchased Tundra autocorrelator system that has higher sensitivity (in addition to a longer scan range). Unfortunately, the Tundra arrived in late September 2019 in need of some repairs from the trans-Atlantic shipment. The repairs were made and the first traces taken in late December 2019. Benchmarking and validation of the device will follow.

Note that a saturable absorber could be added after the final dichroics of the ps-OPA for additional improvements, if an appropriate absorber at 1054nm is easily available. Straightforward Schott color glass options have been used for some time in 800nm systems (such as the J-KAREN petawatt laser system in Japan). In more recent years, the LFEX petawatt laser facility in Japan began to use Cr:YAG as a 1054nm saturable absorber to enhance contrast . Following this approach, samples at 70%, 80%, and 90% transmission in 9.5mm diameter have been ordered from Altos Photonics and are due in January 2020. Again, as we are near the Sequoia sensitivity limit before the improvements offered by a saturable absorber, testing will require the Tundra.

CONTAMINATION:

OBSERVATIONS AND POTENTIAL SOURCES OF CONTAMINATION:

In recent years, distinct contamination in the Target Bay has been observed at 2 locations: on the lens and mirror located west of Chama and on the diverter mirror between Pecos and Conchas, with both being oily and cleanable. The Chama optics were directly connected to that target chamber while the Pecos diverter was isolated from both the Pecos chamber and the Conchas chamber by vacuum windows at each. The contaminations are site-specific or global, with both being plausible. While a global cause seems more likely at first glance, Ella Field reported that the coloration of the wipes that cleaned the films at Chama and at the Pecos diverter were noticeably different (implying perhaps that site-specific contamination is at play). The real concern now is that there is a heightened risk of contamination of the new ZPW compressor multi-layer dielectric gratings (which cannot be cleaned on site). While this is undesirable, it should be mentioned that multiple petawatt-class laser facilities have also admitted to oil contamination issues in their grating compressor vessels.

Based upon the observed locations within the Z-Backlighter facility, the potential sources of contamination are:

- Vacuum stage and/or actuator lubricants,
- Target area contamination unrelated to target interactions (i.e., from 3D printed parts and plastics),
- Target area contamination related to the target interactions (plasma and debris),
- Cryo seal compromise leading to cryo oil exposure,
- Back-streaming of isolating transformer oil from Z,

- General outgassing (from plastics or inadequately cleaned metal hardware/vessel walls) at various points in the system, and
- Anti-seize or vacuum grease.

This is probably not a rigorously complete list. Even if we find a root cause of the contamination, we may not be able to remove that contamination source, especially since multiple sources could be at play or could be event-based rather than chronic. These issues apply to ZBL and ZPW broadly but are of immediate concern as we prepare to activate the ZPW compressor at higher energies. The most worrisome concern of these is the potential for back-streamed oil from Z, which very likely could have Beryllium as well. Although the tube into Z is often blocked at the Switchyard gate valve and a vacuum barrier is present on the tube in the Z Hi-Bay, that tube is routinely removed, which could allow oil to adhere to the interior vessel walls and then back-stream into the Switchyard when the gate is opened. Diagnostic or monitoring methods and mitigation methods for contamination are then needed to address the problem.

MONITORING AND SURVEILLANCE APPROACHES:

For monitoring/surveillance or diagnostics, we propose:

- Tracking the status of various vacuum vessels locally with residual gas analyzers (RGA's):
  - The oil in question from Z is called Diala-X from Shell Oil. An MSDS for it lists 2 consituents: 95 to 100% "distillates (petroleum), hydrotreated light napthenic" and 0.25 to 0.5% "butylated hydroxytoluene" (BHT). The latter is an antioxidant additive with the formula $C_{15}H_{24}O$, which has an atomic mass of 220 a.m.u. per molecule. Thus a mass spectrometer would need to be able to detect >220 a.m.u. in order to check for the BHT in the Diala-X oil. As such, we purchased a residual gas analyzer from Stanford Research Systems (RGA300) capable of detecting up to 300 a.m.u. from $1x10^{-5}$ to $5x10^{-11}$ Torr. To work, the partial pressure from the Diala-X oil would need to be at least $1x10^{-8}$ Torr to detect any BHT at 0.5% or $5x10^{-11}$ Torr. As the overall pressure at the Switchyard is routinely in the $1x10^{-7}$ to $1x10^{-8}$ Torr range and the partial pressure of Diala-X must be a small fraction of that, the chance of detecting any signal from BHT is low. We did run a scan of the Switchyard with the RGA300 but the highest mass species was at 191 a.m.u. at the detection limit. *This does not preclude Diala-X contamination but rather means that BHT cannot be detected.* To get an RGA to give us the information we desire, we either need to detect a more abundant species from the contaminant or we need to sense things at a higher pressure.
  - Regarding detecting a more abundant species from the contaminant, we need to quantify the mass spectral signature. This would involve using the RGA to get a mass spectrum from several key contaminant options and then comparing to what we have in the Switchyard.
  - Regarding sensing at a higher pressure, SRS sells a unit called ULT300 that allows detection from atmospheric pressure down to UHV but it starts at $28K. This could be an idea for often vented areas like the Switchyard but the RGA makes more sense in the areas that stay at high vac.
- Using periodic swipes and testing of optics and vessel walls
  - Ella has found a local outfit named Hall Environmental that can scan swipes via gas chromatography for $50. The idea is to then send them contaminated swipes taken from the Chama lens in order to determine the source. Prior to release, such a swipe was

checked for beryllium and was found to be below the DOE limit. This means that, even if there is Diala-X contamination, there at least is little to no risk of making the Target Bay a beryllium area.

- Two samples were sent to Hall Environmental: a clean unused tissue as a control and one that had been swiped on the contaminated Chama lens. The results (see below) show milliVolts of signal versus the minutes of scan time. The top is the clean tissue as control while the bottom scan is the tissue contaminated with the oily Chama film. Note that the bottom trace shows numerous unknown peaks in the 6.5 to 12minute range. Unfortunately, the peaks are hard to diagnose absolutely. Thus, as with the RGA, it is desirable to get a gas chromatograph from several key contaminant options and then compare them to the Chama sample. This approach is now in process.

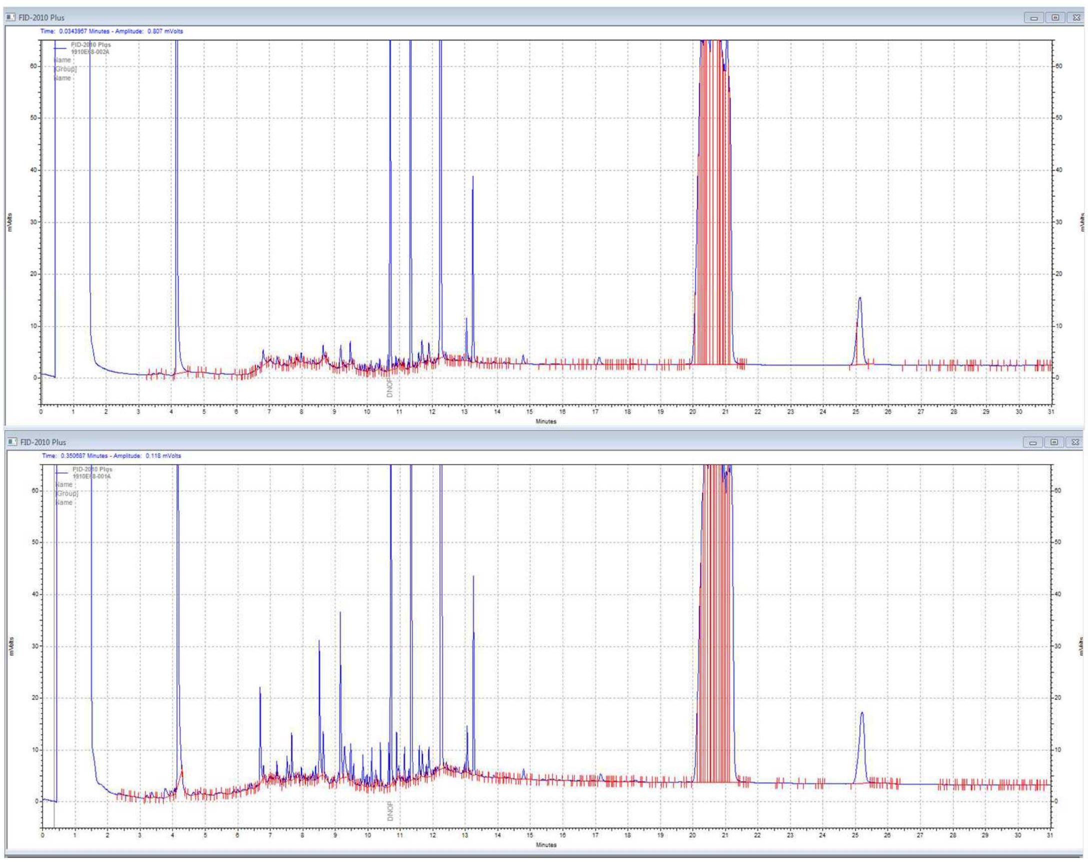


Figure 6. Contamination swipe measurements via gas chromatograph. The top trace is a control scan of the unused wipe while the bottom trace is a scan of the contaminated wipe from the Chama lens. The axes range from 0 to 65mV (vertical) and 0 to 31 minutes (horizontal).

- Using witness samples placed at strategic locations
  - This would probably mean at a minimum placing witness plates at the Switchyard, in the ZPW compressor, at the Chama OAP position, in the Pecos/Conchas diverter, in the Chama diverter, and in each of the big target chambers (Pecos, Chama, Jemez, and Conchas), making for 9 sample positions. If we used 2 at each position (for example with one being an uncoated optic and one being a coated optic, since the dielectric films sometimes act as "catchers"), we could run spectrophotometer scans looking for

transmission changes (or maybe ellipsometer changes in the future), followed by swipes for gas chromatography.

- Employing periodic inspections
    - Where possible, we could periodically inspect key optics and include photo-documentation in situ. We all do this on occasion but a more systematic approach may be a good idea. Standard bright light illumination and UVA (blacklight) inspection are advised. UV lights in the 350 to 400nm range are known to cause oils and hydrocarbon contaminants to fluoresce strongly.

MITIGATION AND ELIMINATION APPROACHES:

For mitigation and/or elimination, we propose:

- Employing pellicle debris shields in the beam path
    - This can stop debris and reduce line-of-site contamination from gaseous flow but would not be a hard seal like a vacuum window. We would consider them at the gate valve entrance to Chama and at the ZPW compressor exit. The B-integral is low because it is so thin: For 10μm thickness at n2=3E-16 cm^2/W and a 1054nm intensity of $1PW/800cm^2=1.25TW/cm^2$, B=0.02 radians. We found AR nitrocellulose pellicles up to 17cm diameter at 1.8um thickness with single-shot 500fs LIDT's of $2.2J/cm^2$. Unless we can find larger diameter pieces, this might not work at the ZPW compressor because a 28cmX31cm beam has a diagonal of 42cm (which leaves minimal clearance at the current pellicle clear aperture of 42.5cmϕ). It would work fine at the entrance to Chama due to the converging beam. Also note that, at 1.8μm thickness, the round trip delay would be 2*n*L/c=2*1.5*1.8μm/(0.3um/fs)=18fs, which is within the pulsewidth, meaning that a true pre-pulse would not be generated and contrast would not be degraded.
- Using silica gel as "catchers" in areas of known contamination risk
    - Professor Jitsuno at the LFEX petawatt laser in Osaka published several SPIE proceedings on the subject of using silica gel in vacuum compressor vessels to absorb the contaminant oil vapors (regardless of the source). Ella followed up with him recently to find out some details, including the fact that the approach is still in use at LFEX. This seems entirely manageable at Sandia and would be appropriate in the grating compressor mainly.
    - The appropriate source for silica gel of suitable quality is being explored. We would need between 50 and 100 lbs. of silica (based upon the guidance of Professor Jitsuno).
- Use periodic cleaning where possible
    - In a position like the OAP, in situ cleaning might be a good idea as I believe this could be done with acetone and methanol wipes. With any luck, the OAP will not damage due to oily film contamination but this is truly an unknown. Some studies show significantly lowered LIDT's (depending on the type of organic contaminant) while others don't.

FORWARD PROGRESS IN THE COMPRESSOR AND BEYOND:

The compressor work has resumed, using the argument that the contamination deposition will be worse in vacuum and that initial alignment can begin with the ZPW compressor exit gate valve closed and the chamber vented. In this mode, we have (see Figure 7):

- Aligned the input telescope into the ZPW compressor (pending collimation adjustment).

- Mounted beam dump glass in newly constructed frames. These are designed to catch specular grating reflections, thereby avoiding the risk of wall ablation and deposition on nearby optics.
- Mounted the off-axis parabola for Chama in its bezel and mount. This is an f=1.7m 57cmϕ OAP coated at Sandia. Over the 2019 Winter shutdown, the OAP will be installed into its position at Chama. When aligned, the anticipated diffraction-limited spotsize is 5.8μm FWHM X 6.8μm FWHM, making for an ideal peak irradiance of $2 \cdot 10^{21}$ W/cm^2 at 1PW peak power.
- Begun alignment of the ZPW compressor gratings. The mounted optics have had their protective seals removed and the motion control validated.

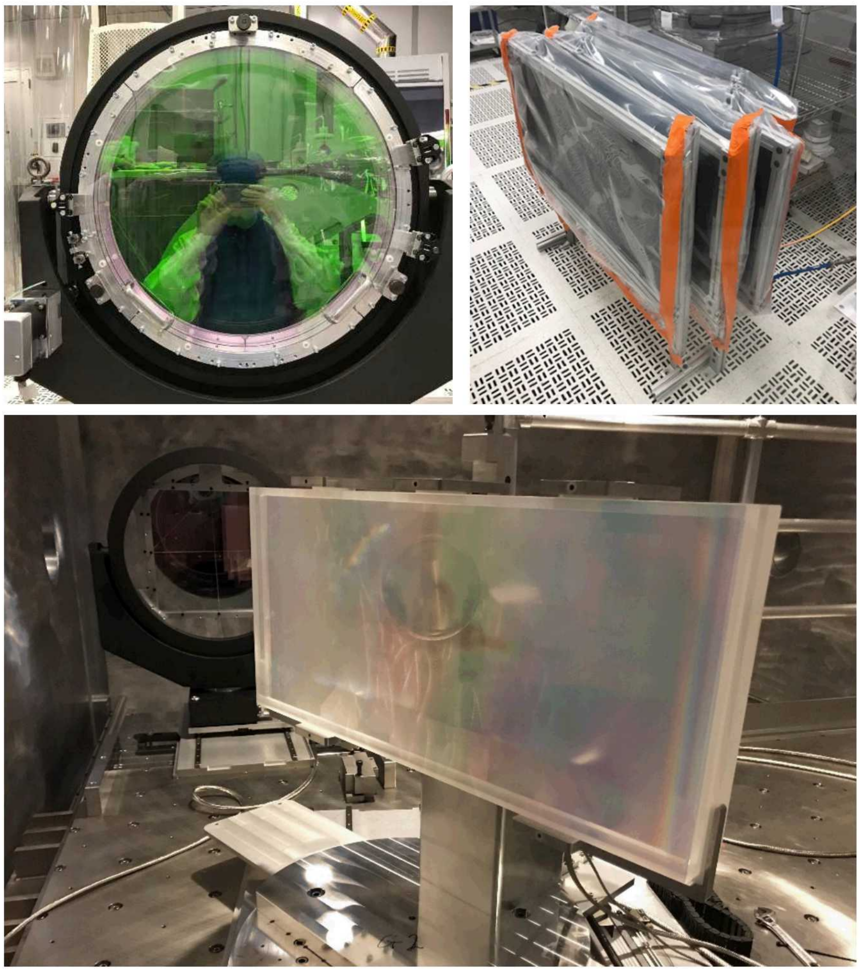


Figure 7. (Upper left) The mounted Chama OAP. (Upper right) The “bagged” compressor beam dumps. (Bottom) On the left (in the background) is the output lens of the relay telescope into the compressor. In the foreground is the installed and “unbagged” G2 grating (42cm X 94cm multilayer dielectric).

Another related activity is to assess the status and feasibility of long-term operations for the ZPW final optics assembly (FOA). The FOA contains another OAP and fold mirror and is a complex system with up to 6 axes of motion control and multiple methods of protecting against Z shocks, debris, and contamination. The system was built years ago but suffered greatly from complexity and “ease of use” issues. It is currently in a tented area within the Z Hi-Bay, with the tent qualifying as a beryllium contamination control area (BCCA) and a radiation area (see Figure 8). These complexities have required certain ZPW team members to get additional trainings and authorizations prior to the initial assessment and work. In the meantime, the engineering requirements and recommended corrective measures have been documented.

Figure 8. Views of the ZPW FOA in the BCCA tent from the north (left) and south (right).

MOVING INTO CY2020:

In addition to supporting various experimental campaigns in CY2020, the following is a non-exhaustive list of planned ZPW work:

- To align the newly installed full-aperture co-injection fold mirror and perform conditioning shots with the goal of achieving >1kJ at 527nm. This will open up new experimental options, including the possibility of additional energy for MagLIF and additional backlighter frames. Timeframe: Q1 of CY2020
- To continue with the diagnosis of the contamination issues and implement best-practices monitoring and mitigation efforts. Timeframe: Q1 and Q2 of CY2020
- To complete the ZPW compressor alignment and begin ZPW calibration full-system shots. Timeframe: Q1 of CY2020
- To align the Chama OAP and begin ZPW experimental activities in Chama. Timeframe: Late Q1 of CY2020
- To complete the development of the contrast enhancement system. Timeframe: Q3 of CY2020
- To assess the ZPW FOA status and develop a definitive plan forward. Timeframe: Q1 of CY2020
- To develop and test a coordinated motion system that allows optimization of complex multi-actuator motion in the ZPW FOA.   Timeframe: Q3 of CY2020
- To develop and test an FOA off-line pre-alignment system. Timeframe: Q3 of CY2020

ACKNOWLEDGMENTS

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