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Title:	Characterization of the Los Alamos IPG YLR-6000 Fiber Laser Using Multiple Optical Delivery Paths and Laser Focusing Optics
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Intended for:	Distribution to NNSA Lab and AWE participants as part of the LANL LLNL AWE Enhanced Collaboration for Welding

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Characterization of the Los Alamos IPG YLR-6000 Fiber Laser
Using Multiple Optical Delivery Paths and Laser Focusing Optics

J.O. Milewski, J. E. Bernal

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Summary:

Fiber laser technology has been identified as the replacement power source for the existing Los Alamos TA-55 production laser welding system. An IPG YLR-6000 fiber laser was purchased, installed at SM-66 R3, and accepted in February 2008. No characterization of the laser and no welding was performed in the Feb 2008 to May 2009 interval. T. Lienert and J. Bernal (Ref. 1, July 2009) determined the existing 200 mm Rofin collimator and focus heads used with the Rofin diode pumped lasers were inadequate for use with the IPG laser due to clipping of the IPG laser beam. Further efforts in testing of the IPG laser with Optoskand fiber delivery optics and a Rofin 120 mm collimator proved problematic due to optical fiber damage. As a result, IPG design optical fibers were purchased as replacements for subsequent testing. Within the same interval, an IPG fiber-to-fiber (F2F) connector, custom built for LANL, (J. Milewski, S. Gravener, Ref.2) was demonstrated and accepted at IPG Oxford, MA in August 2009. An IPG service person was contracted to come to LANL to assist in the installation, training, troubleshooting and characterization of the multiple beam paths and help perform laser head optics characterization. The statement of work is provided below:

In summary the laser system, optical fibers, F2F connector, Precitec head, and a modified Rofin type (w/ 120mm Optoskand collimator) / Window / Boot system focus head (Figure 1) were shown to perform well at powers up to 6 kW CW. Power measurements, laser spot size measurements, and other characterization data and lessons learned are contained within this report. In addition, a number of issues were identified that will required future resolution.

Statement of Work for IPG:

Los Alamos National Laboratory requests the troubleshooting and characterization of its IPG YLR-600 laser, beam delivery system, laser collimators, and focusing heads. Recent optical fiber damage has identified the need to better understand and demonstrate the system performance over a full range of operating conditions.

This statement of work includes the service of a communication module for the laser, a full testing of laser and IPG F2F connector interlocks and E-stops, and a demonstration of power ramping and beam modulation is required.

We request an IPG service representative to assist and oversee LANL personnel in the following areas:

- Verify the power transmission performance and the stray light interlocks of the IPG fiber-to-fiber coupler.
- Characterize laser power and collimated beam at various locations of both channel 1 and channel 2 beam delivery paths. This will include measurements at the output of 200 micron fibers connected to channels 1 and 2, at the output of the IPG fiber-to-fiber coupler using 300 micron fibers. This will be performed using LANL supplied Primes Power Monitor and Primes Beam Monitor over a range of power for characterizing power loss and beam size.
- Characterize laser power, collimated beam, and focused beam at the output of both a Precitec collimator and laser head up to 6 kW CW power and a Rofin 120 mm collimator and laser head up to 3 kW of CW power. This will be performed using LANL supplied Primes Power Monitor, Primes Beam Monitor, and a Primes Focus Monitor over a range of power for characterizing power loss and beam size.
- Oversee weld demonstrations using both delivery paths on stainless steel test plates.
- Oversee laser / CNC motion control demonstrations using the AeroTech / IPG CNC interface.
- Demonstrate the robustness of the laser and beam delivery systems to the actuation of all interlocks, E-stops and the delivery of beam modulated laser power for a variety of pulse and ramp waveforms.

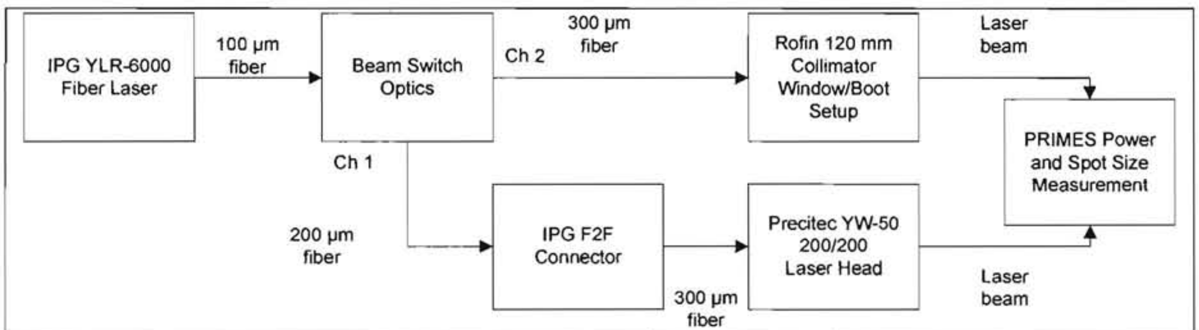


Figure 1. Schematic of the two channel LANL IPG YLR 6000 optical paths

Laser communication, interlock and interface troubleshooting

A laser startup problem found during the July to August 2009 testing was identified to be an unconnected interlock wire making intermittent contact with its terminal and resolved prior to the IPG service visit.

Upon initial testing it was determined that the water cooling interlocks for channel 1 were being monitored by the system (as set up for the Optoskand coupler) while laser power was being tested on the channel 2 beam path. This was resolved by completing the chill water circuit through the channel 2 plumbing and interlock chain. This did however indicate the LaserNet software is unable to resolve between the interlocks of one channel verses the other. This condition could have led to optical fiber damage due to overheating and would need to be resolved in future specification of the laser control interface for a production system.

Another LaserNet interface problem was identified associated with the Emission ON indicator light. Below a certain threshold of generated power, <10% for all modules, the Emission indicator indicated OFF while laser power was being generated and delivered to the power meter. *<u>Therefore the LaserNet Emission indicator should not be relied upon to indicate a laser safe condition.</u>* All of our laser safety controls and procedures are however based upon the condition of laser power to the system (as indicated by the flashing light upon the top of the laser) and not based upon an indication of the software interface and is deemed a non-critical error to be addressed in a production control software interface.

Another potential LaserNet issue can depend on your PC mouse control setting. If inadvertently positioned along the power selection bar within the Laser Net interface, a <u>full power setting may be accidently selected.</u> **This *does not* turn on the selected power but immediate resolution of the problem is required by setting the Windows mouse control to require a double click selection.**

Demonstration of the IPG laser control using the Aerotech motion controller interface resulted in the shorting of signal pins, a blown fuse in the laser, and the crashing of the hard drive on the IPG laser's on board computer. The hard driven was replaced by a flash memory module. As a result the laser power calibration lookup table had to be regenerated prior to the power modulation study. Calibration of the laser net indicated power will ultimately need to be calibrated at some point along the optical path chosen for a specific configuration. It also points to the need to offline save the laser power calibration table (and calibration procedure settings and locations) for future reference.

During one of the power runs with the modified Rofin (120 mm Optoskand) head the laser stopped without warnings. The laser chill water flow threshold was set too low for the process fiber input. This was indicated in the Information LOG where the beam switch mirror was logged to have switched between channel 2 and "home" position multiple times in less than a second. Flow indicators were seen to flash ON and OFF but did not "latch" the condition. We raised the pressure and opened the flow set point setting to (one) 1 lpm.

<u>Laser Power and Spot Size Measurement</u>

A PRIMES PM 48, SN# 3994 power meter (purchase date 2008) was used to measure laser power up to 6 kW. Building water flow was adjusted to 8 lpm.

A PRIMES 120, SN# 22120 focus monitor with tip # 4630 (purchase date 2005) was used with argon gas for the Rofin (Window / Boot Optoskand, 120 mm collimator) measurements and He gas for the Precitec measurement each at 25 cfh. Version 2.73.1.5 of the PRIMES focus monitor software was used.

A PRIMES 60 SN# 1834 purchase date 2005) beam monitor was used to measure the collimated beam size of the Rofin (120 mm Optoskand) collimator.

<u>Characterization of the Rofin (Optoskand 120 mm) collimator and Window / Boot Setup</u>

Figure 2 taken from Ref. 1 shows the LANL TA-55 PF-4 production Window / Boot setup, the SM-66 R3 laser lab mock up test station and 120 mm Rofin Optoskand collimator.

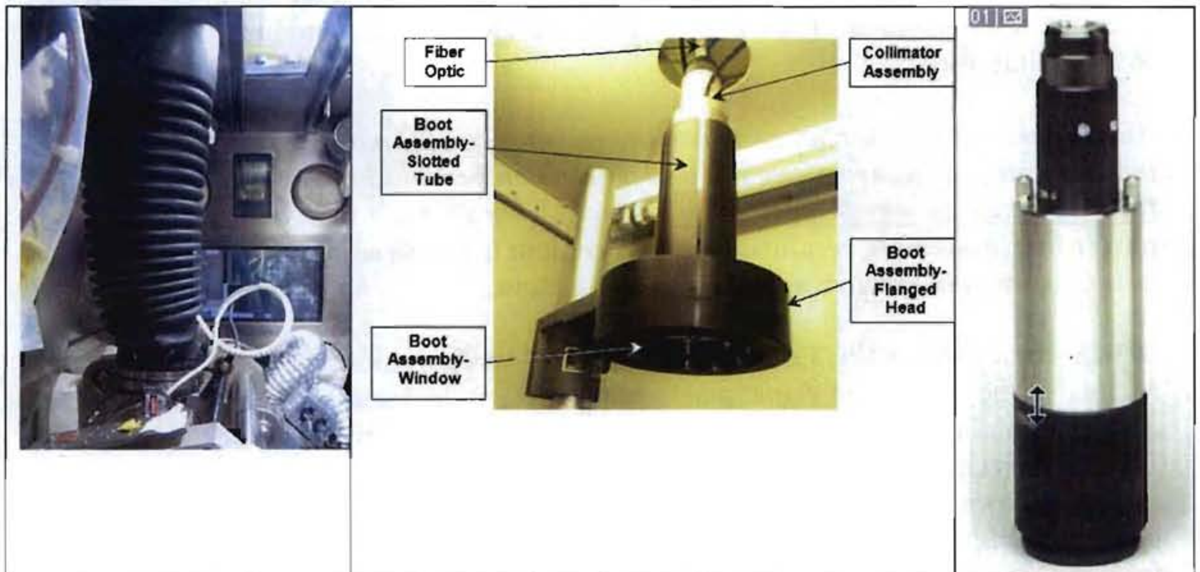
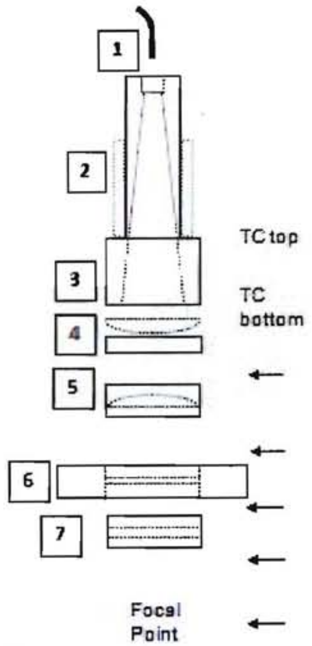


Figure 2. a) TA-55 Production Window / Boot set up	b) Production Mock Up Test Station at SM-66	c) Rofin type Optoskand 120 mm collimator.

A 300 μm diameter 10 meter length IPG optical fiber (Fig. 1) was cleaned, installed in beam switch channel 2, and aligned according to procedures documented in Ref. 3 (J. Milewski).



Component	Description
1	Fiber Optic Cable
2	Collimator Cooling Jacket
3	Collimator Body
4	Collimator Lens & Ring
5	Focus Lens Assembly
6	Boot Window
7	Cover Glass Assembly

Figure 3. Window / Boot optical elements and characterization locations shown by arrows.

The optical elements shown in Fig. 3 were characterized at various power levels and at the locations show by arrows to include various of the optical elements to determine power losses. Temperature rise at two locations was measured by the attachment of type K thermocouples on the outside of the collimator assembly shown in Fig 2c.

Window / Boot Characterization	Rofin 120 mm Collimator, 200 mm focal lens
Collimated beam diameter mm, with 300µm fiber	8.8 mm @ 500, 1000W, 8.7 mm at 2000, 3000 W
Focal spot radius in mm w/ 200 mm fl Focal spot radius in mm w/ 160 mm fl	~ 0.244 mm ~ 0.203 mm
Percent Power loss – collimator only verses all optical elements at ~ 500 W and ~ 2.5 kW in %	@ 500W < 2 % @ 2500 < 2%
Collimator Temp rise from ~250W to ~ 3kW	less than 3 degrees C
Collimator Temp difference between bottom TC at 1.5" up and bottom TC 0.3" up at ~ 3kW	~ 1 degree C
Figure 4. Window / Boot Statistics	

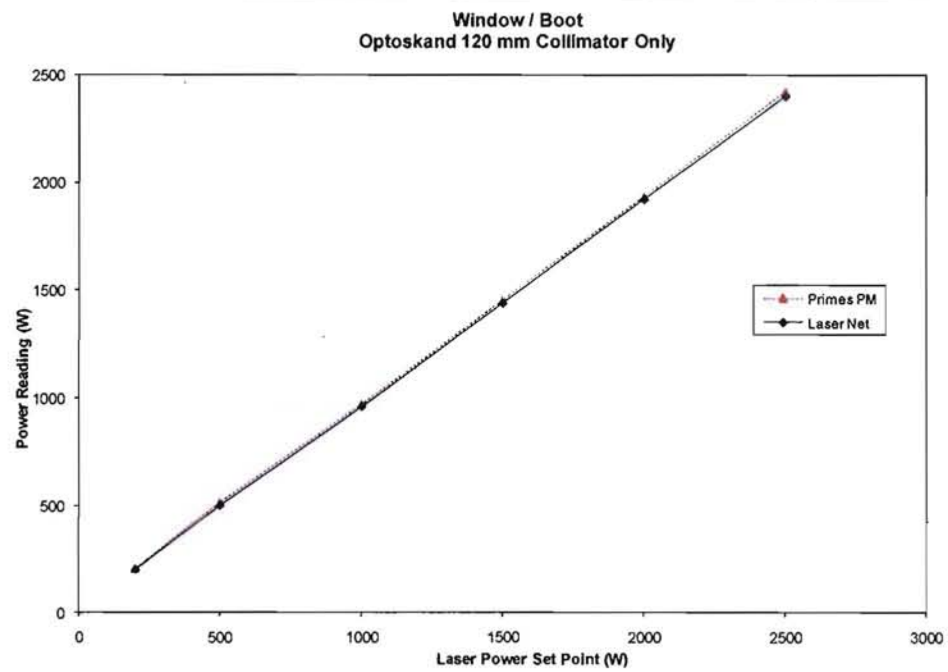


Figure 5. Set point power vs. Laser Net power and Primes power relationship is linear.

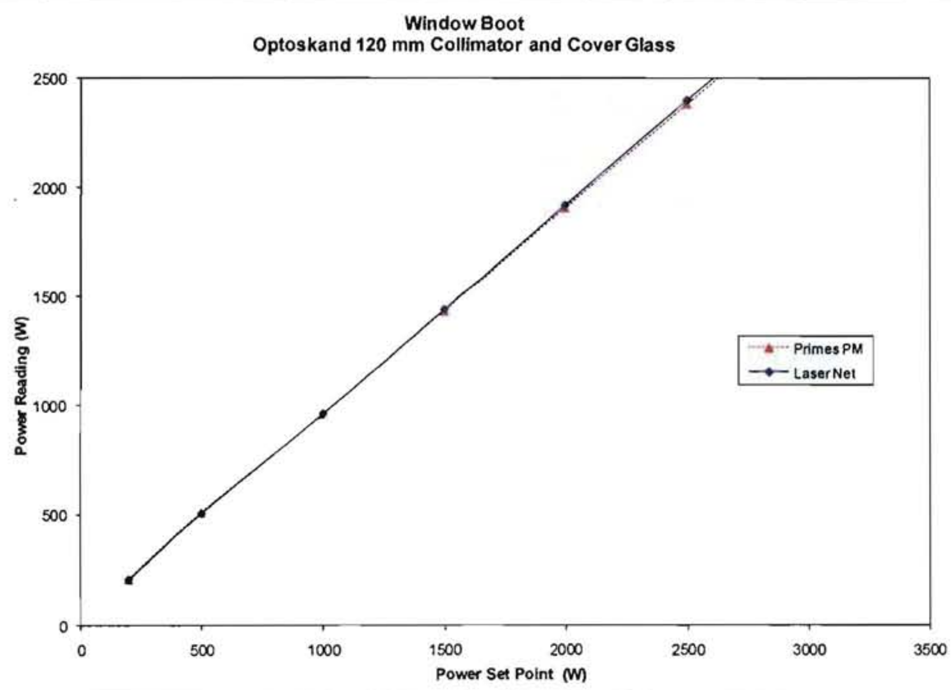


Figure 6. Window / Boot power reading with cover glass added shows little loss.

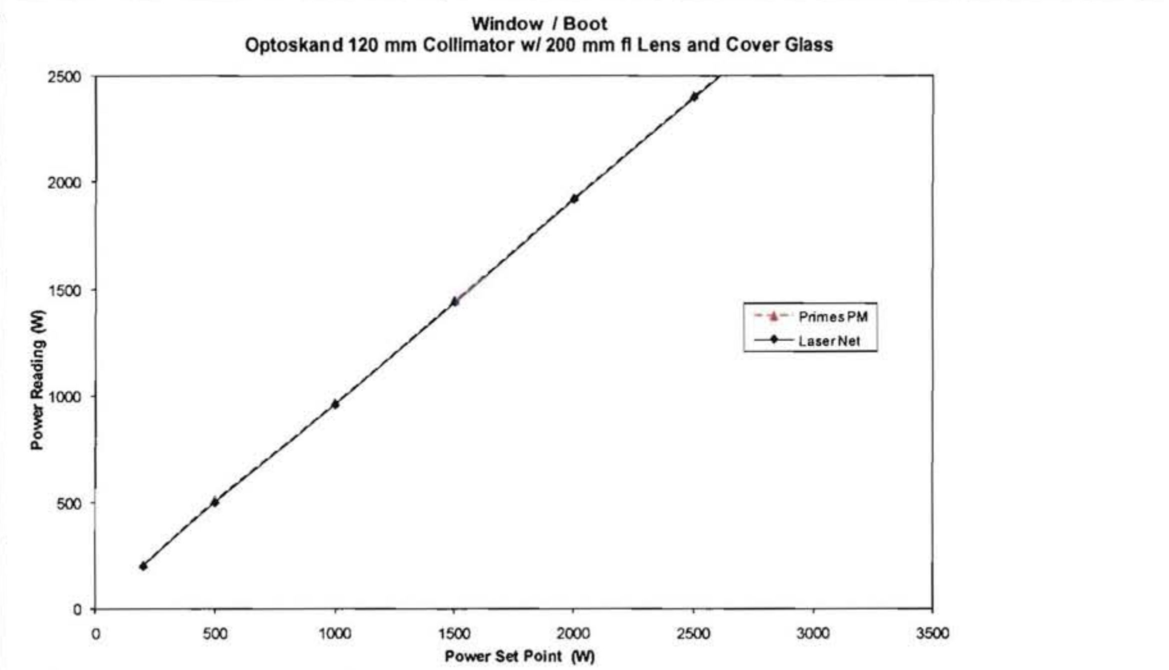


Figure 7. Addition of the 200 mm focus lens has little effect on power loss.

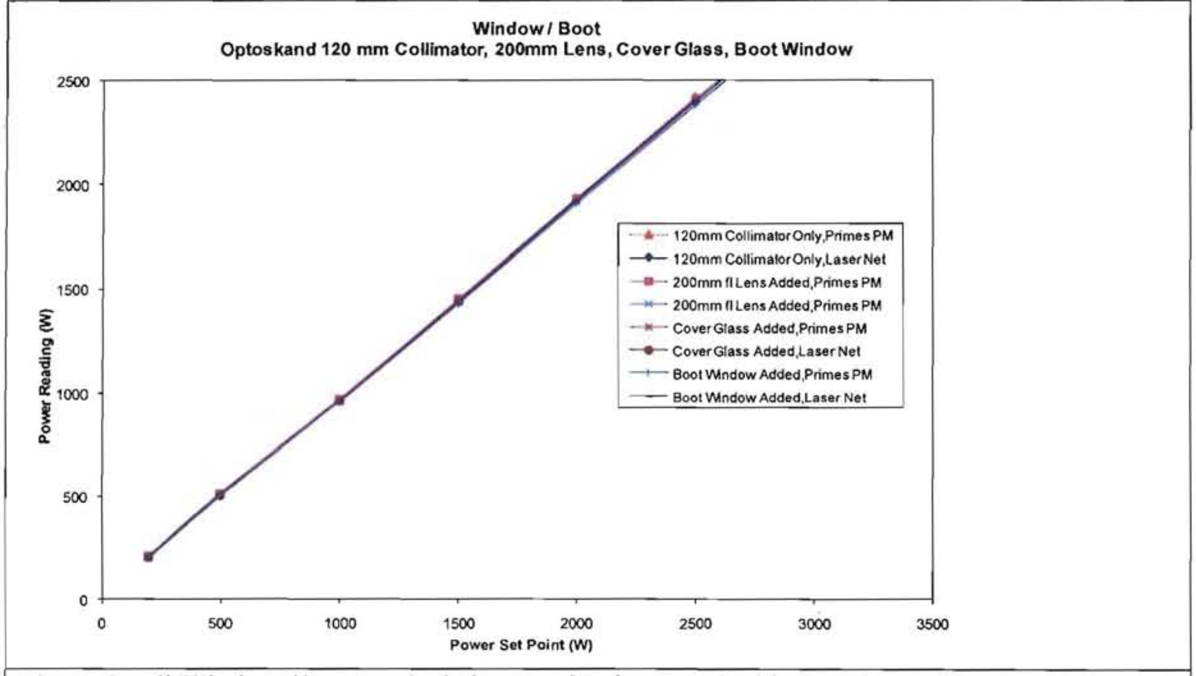


Figure 8. All Window / Boot optical elements in place resulted in less than a 2% power loss.

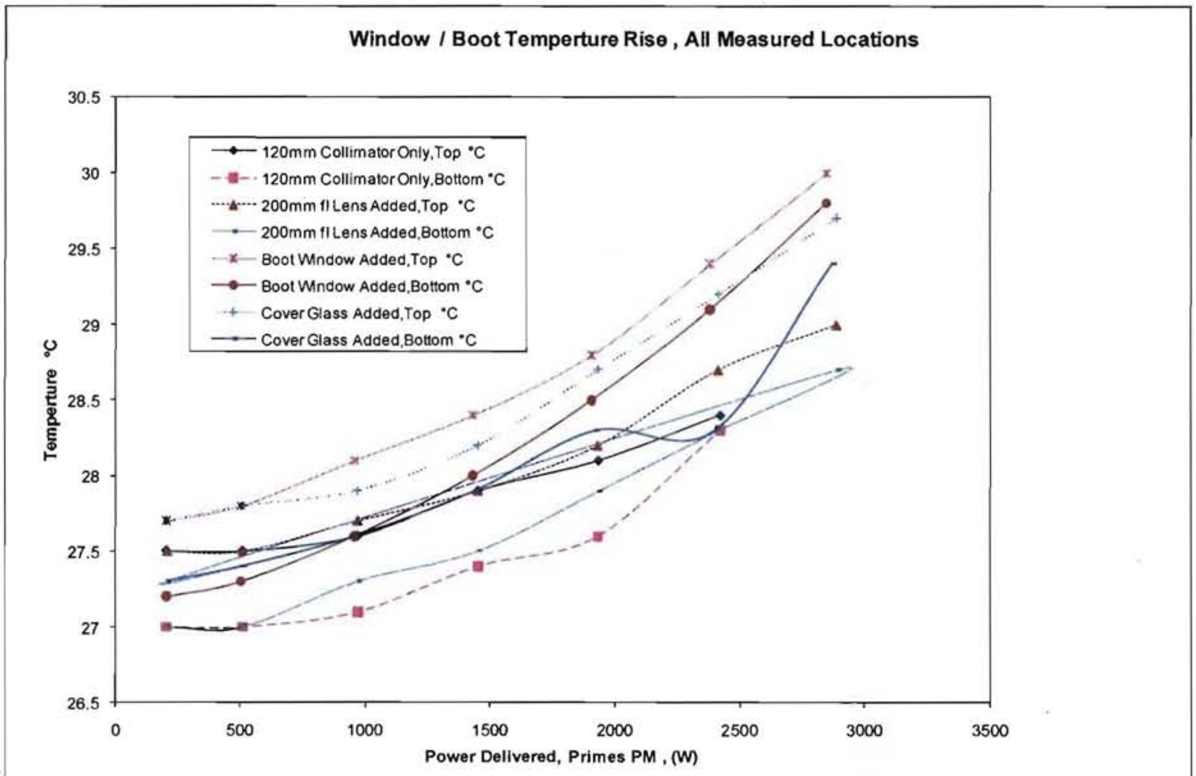


Figure 9. Top TC was hotter by less than °C, < 3 degrees C rise over 2500 W.

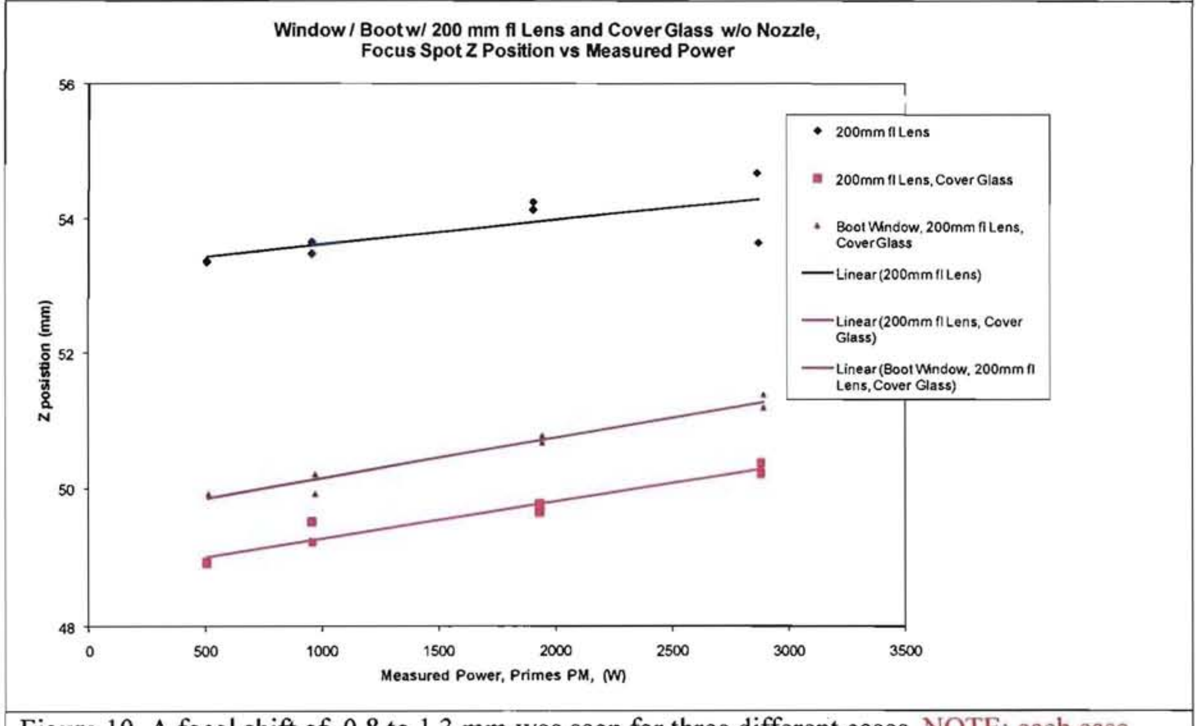


Figure 10. A focal shift of 0.8 to 1.3 mm was seen for three different cases. NOTE: each case involved a reposition of the laser head in Z so comparisons between cases is not valid.

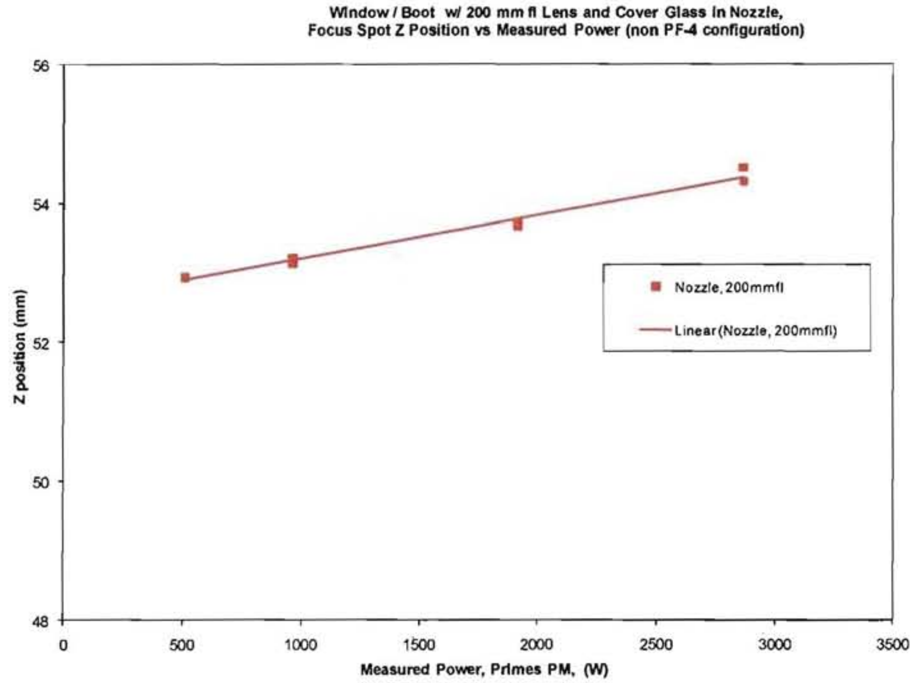


Figure 11. A linear Z shift of 1.6 mm was seen when increasing power from 500 to 3000 W with all optical elements in place. Adding optical elements increases Z shift.

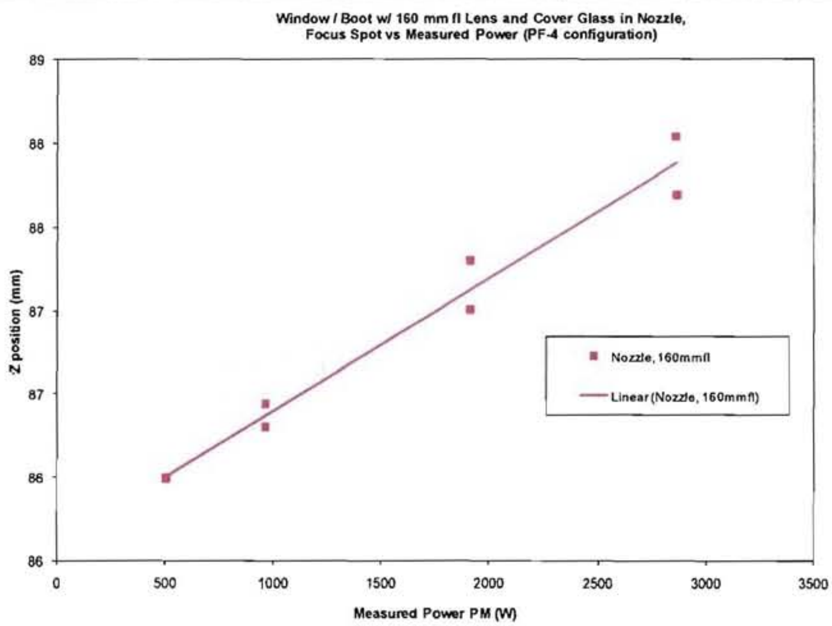


Figure 12. A linear Z shift of 1.87 mm was seen when increasing power from 500W to 3000 W and is greatest with the cover glass in the TA-55 location (lowest, toward weld)

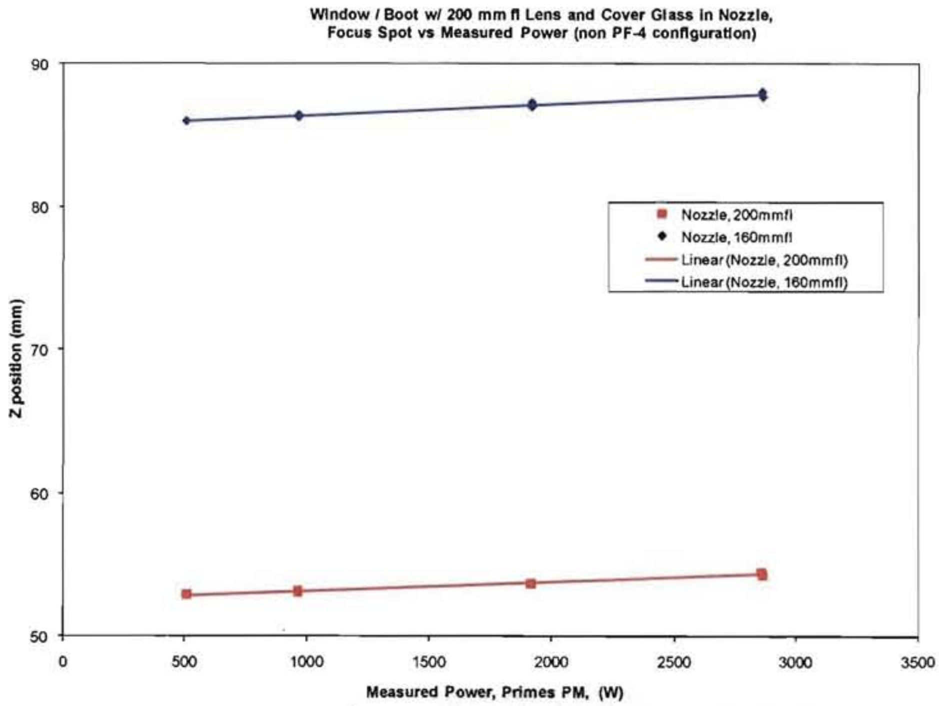


Figure 13. Z shift 1.87 mm w/ 160 mm fl, Z shift 1.38 mm w/ 200 mm fl . NOTE: each case involved a reposition of the laser head in Z so comparisons between cases is not valid.

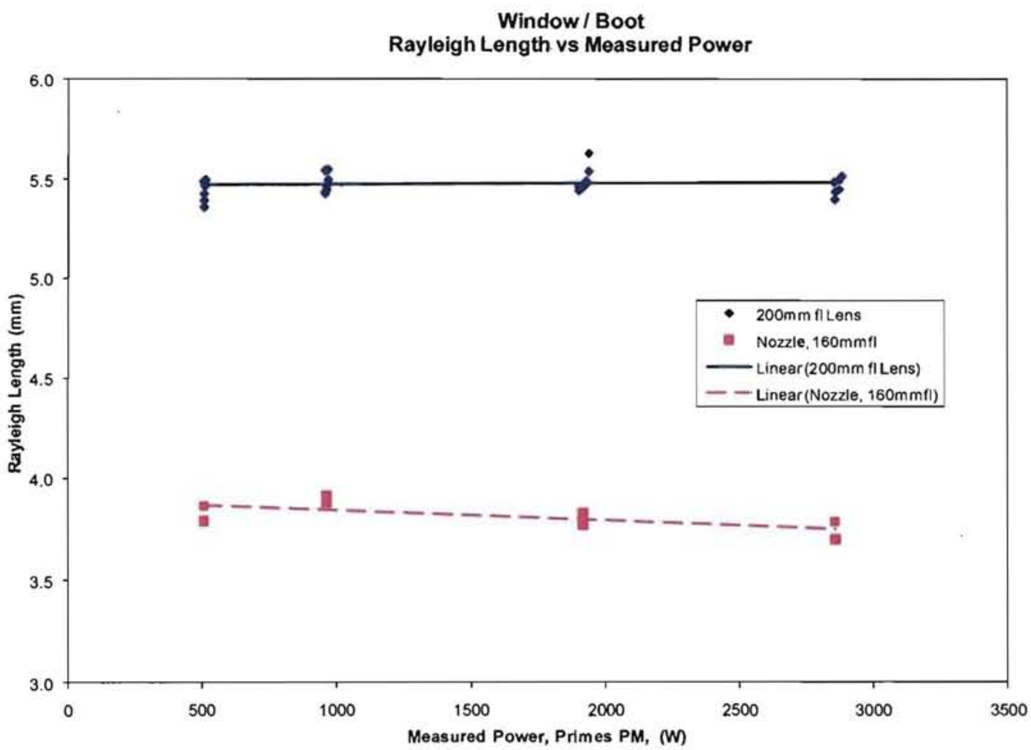


Figure 14. Rayleigh length remains fairly constant and is shorter for the shorter focal length lens.

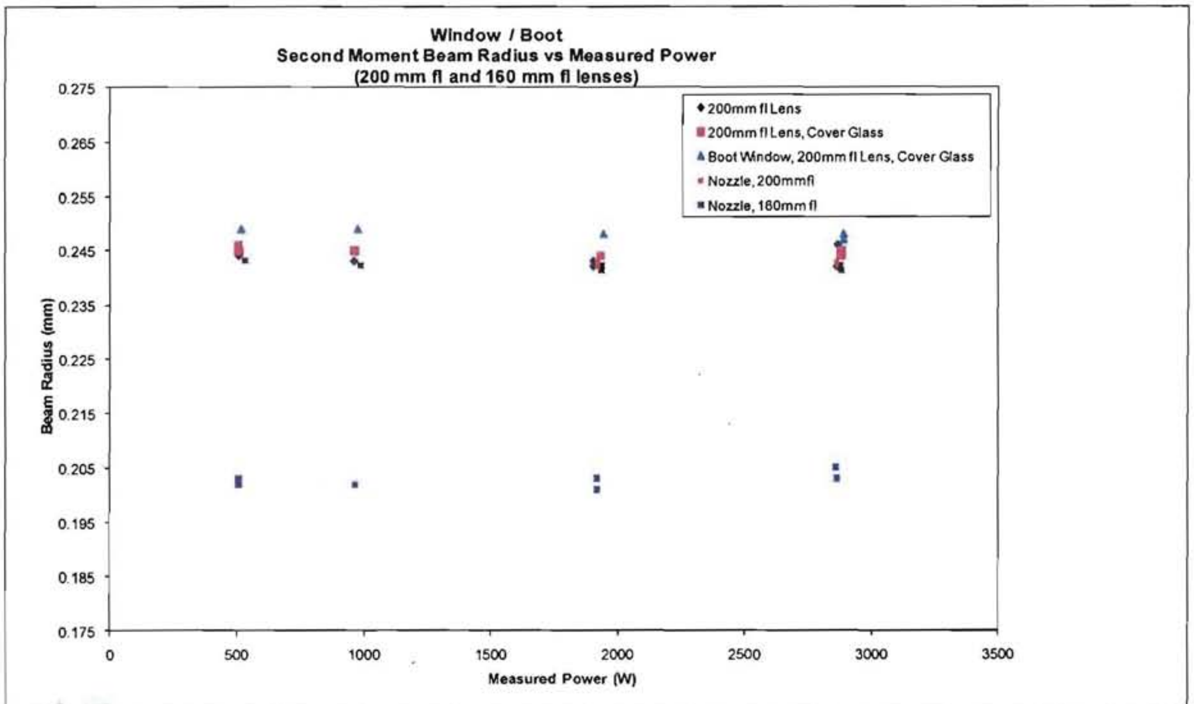


Figure 15. The 160 mm fl focused to a small spot size.

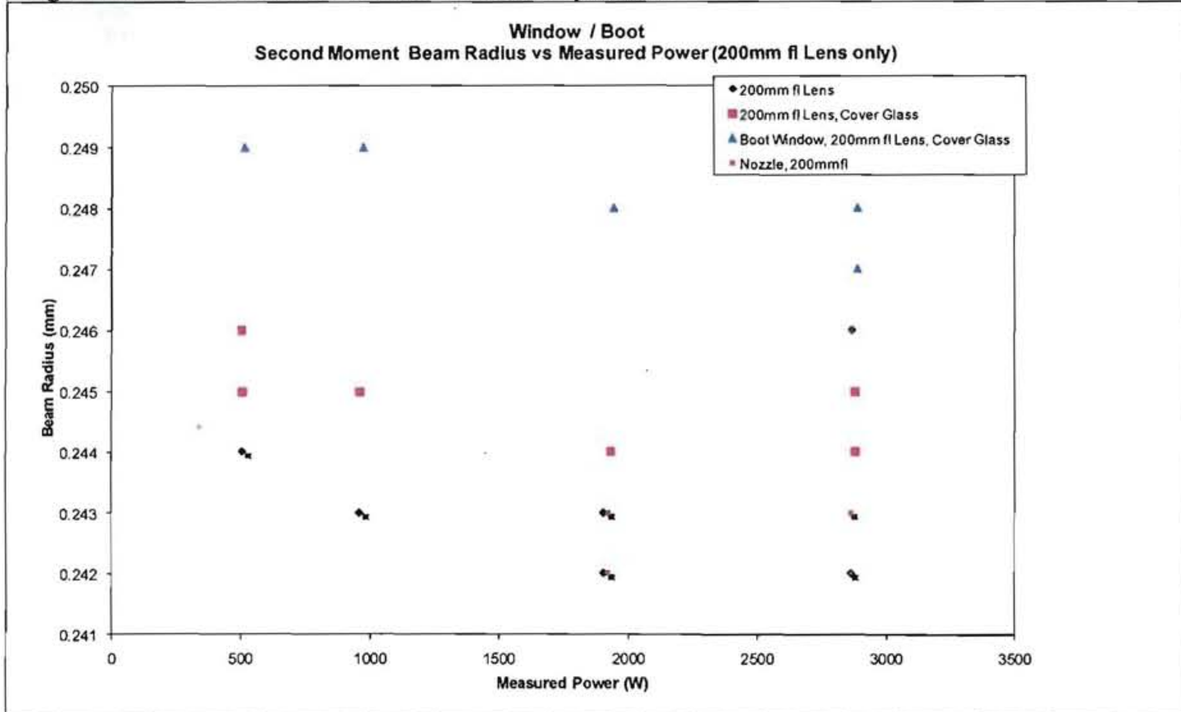


Figure 16. Expansion of data for the 200 mm fl lens indicates the addition of optical elements increased the spot radius.

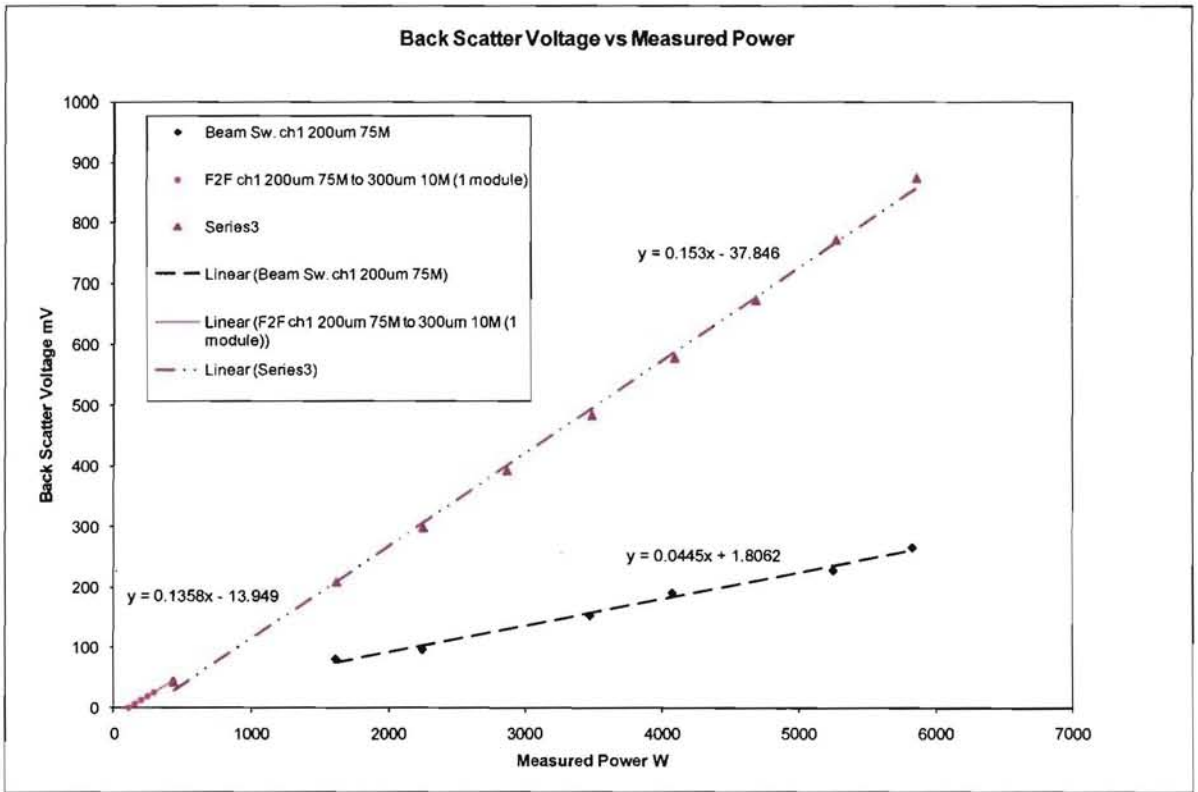


Figure 17. Back scattered light was measure at both the beam switch and F2F connector.

Demonstration Weld

A weld onto a stainless steel bar was demonstrated to the program office using the Window/Boot configuration demonstrating the feasibility of this optical setup to be integrated directly into the existing TA-55 PF-4 hot or cold laser weld glove boxes.

Scatter Light Measurement at the Beam Switch and F2F connector
LN = Laser Net, PM = PRIMES power meter, VOM = Fluke VOM meter

ID	Number of Modules used	Power			Scattered Light		
		Percent	LN	PM	VOM [mV]	Laser Net [mV]	Trans[%]
Rofin Head	13	50			133		
	13	100		6113	266		
	13	100	6070	6120	281		
Beam Sw. ch1 200um 75M	1	50	210	205	15.1		
	1	60	270	259			
	1	70	310	309			
	1	100	460	438			
Beam Sw. ch1 200um 75M			1670	1606	79.1	76	96.2
			2330	2243	95		96.3
			3610	3470	152		96.1
			4240	4070	190		96.0
			5470	5251	228		96.0
			6090	5830	266	278.1	95.7
F2F ch1 200um 75M	1	20	120	108	0.3		90.0
to 300um 10M	1	40	170	156	7.6		91.8
(1 module)	1	50	220	205	13.5		93.2
	1	60	270	246	20		91.1
	1	70	310	298	26.7		96.1
	1	100	450	436	45		96.9
(all modules)	13	30	1670	1614	210		96.6
	13	40	2300	2251	300		97.9
	13	50	2970	2868	393		96.6
	13	60	3610	3486	485		96.6
	13	70	4230	4087	579		96.6
	13	80	4850	4680	674		96.5
	13	90	5460	5270	773		96.5
	13	100	6090	5854	875		96.1

Table 2. Scattered Light as a function of beam power at the beam switch and F2F.

Characterization of the Precitec Head and IPG F2F Coupler

The Precitec laser welding head is shown in Figure 18 a with the PRIMES focus monitor and power meter positioned below. Figure 18 b shows the IPG optical fiber used between the F2F connector and the Precitec head. Note the tightly coiled "strain relief" feature at the input side of all new IPG fibers and the required water cooling lines for both the fiber ends and laser head.

The Channel 1 (Fig. 1) beam path was initially configured without the F2F connector, plugging the 200 micron, 75 meter Optoskand delivery fiber directly into the laser head, characterizing power to 6 kW. Focal spot size was only characterized to 1.5 kW to avoid exceeding the 6 MW / cm^2 maximum power density rating of the focus monitor.

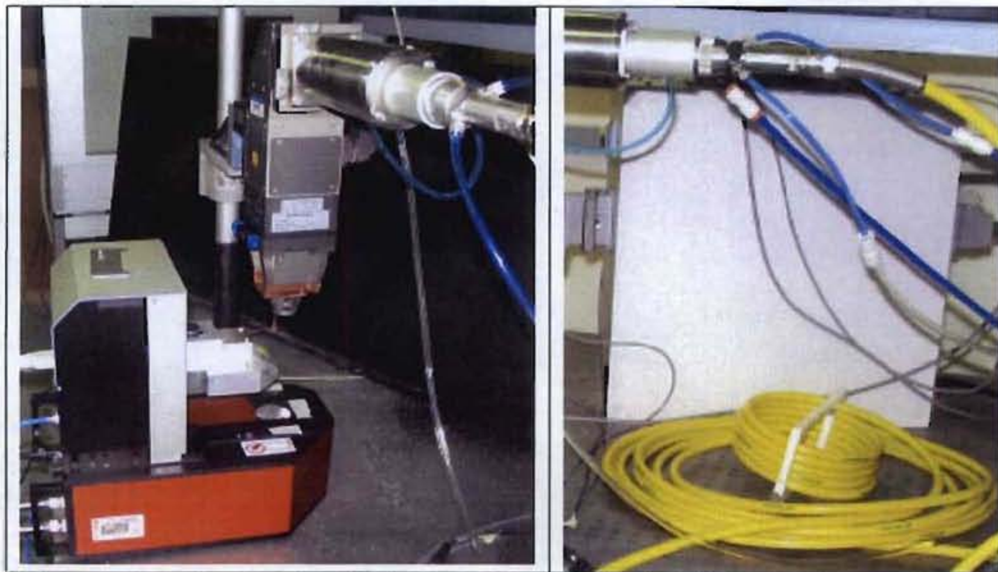


Figure 18. a) The Precitec head setup with PRIMES focus monitor and PRIMES power meter.	b) Strain relief coil shown on the input end of the fiber. And the support coil on the output end of the fiber at the bayonet base.

The Channel 1 full optical path configuration was characterized using the IPF F2F coupler shown in Figure 19. The chiller, interlock controls, and flow controls are shown in Figure 20. This is a fairly complex set of controls that are tied back into the IPG laser interlock chain. The interlock and flow control identification provided by IPG for the F2F is given in Appendix A.

The Precitec laser head was configured with a 200 mm collimator and 200 mm final focus lens and cover lens. No shield gas was used as all the power was being dumped into the PRIMES power meter. The Edison Welding Institute has suggested a thin film of vapor, that may not be visible, is sometimes enough to create focal lens or cover glass heating and damage. Shield or shear gas protection was not deemed needed as no welds were made using this setup due to time constraints, but are planned for the future.

A series of measurements were made to characterize the Precitec laser head with and without the F2F connector. Power loss measurements were made as well as characterizing the beam spot size , Rayleigh length and Z shift for various of the optical combinations. Data is provide in Table 3 and Figs 21-25.

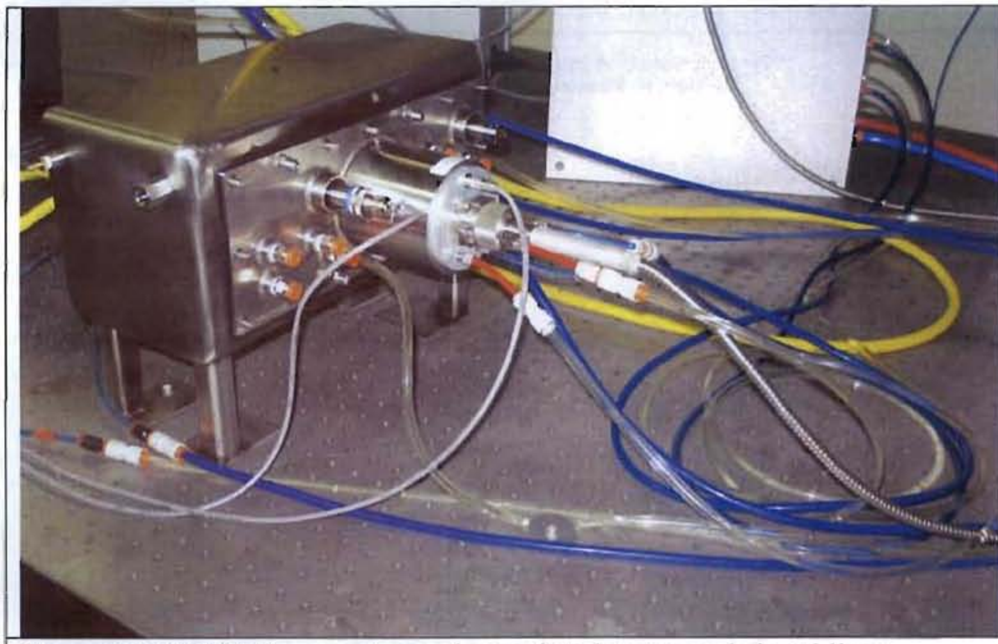


Figure 19. IPG F2F connector and associated water and signal lines.

Figure 20. Two water chillers, interlocks, and control cabinets for the F2F.

F2F Precitec Head Characterization	200 mm collimator, 200 mm focal lens
Focal radius in mm w/ 200 mm fiber direct Focal radius in mm w/ F2F and 300 μm fiber	~ 0.103 mm ~ 0.147 mm
Percent Power loss – 200 mm fiber direct optical Percent Power loss -- F2F and 300 μm fiber	@ 6 kW < 2 % @ 6 kW < 2%
Z focal shift in mm w/ 200 mm fiber direct Z focal shift in mm w/ F2F and 300 μm fiber	0.27 mm 200 to 1400 watts 0.21 mm 200 to 1400 watts
Table 3. Precitec head statistics	

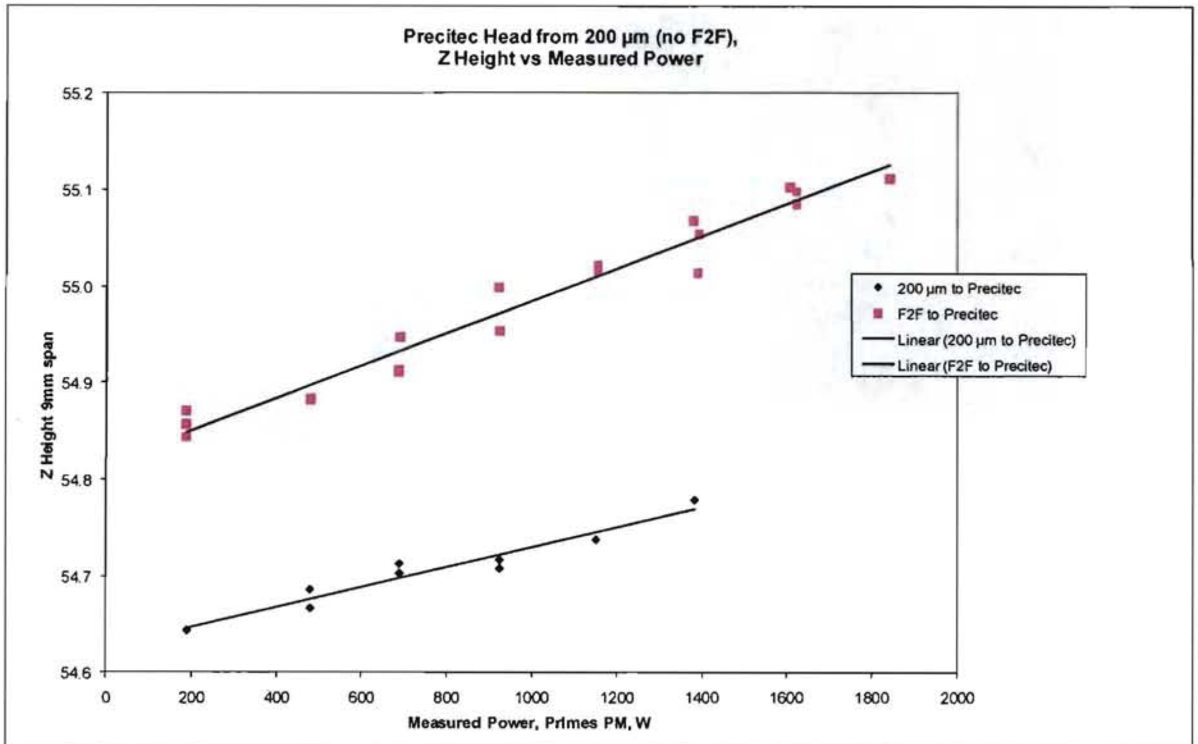


Figure 21. A Z height shift in the laser focus of nearly 0.3 mm was seen using the F2F optical path.

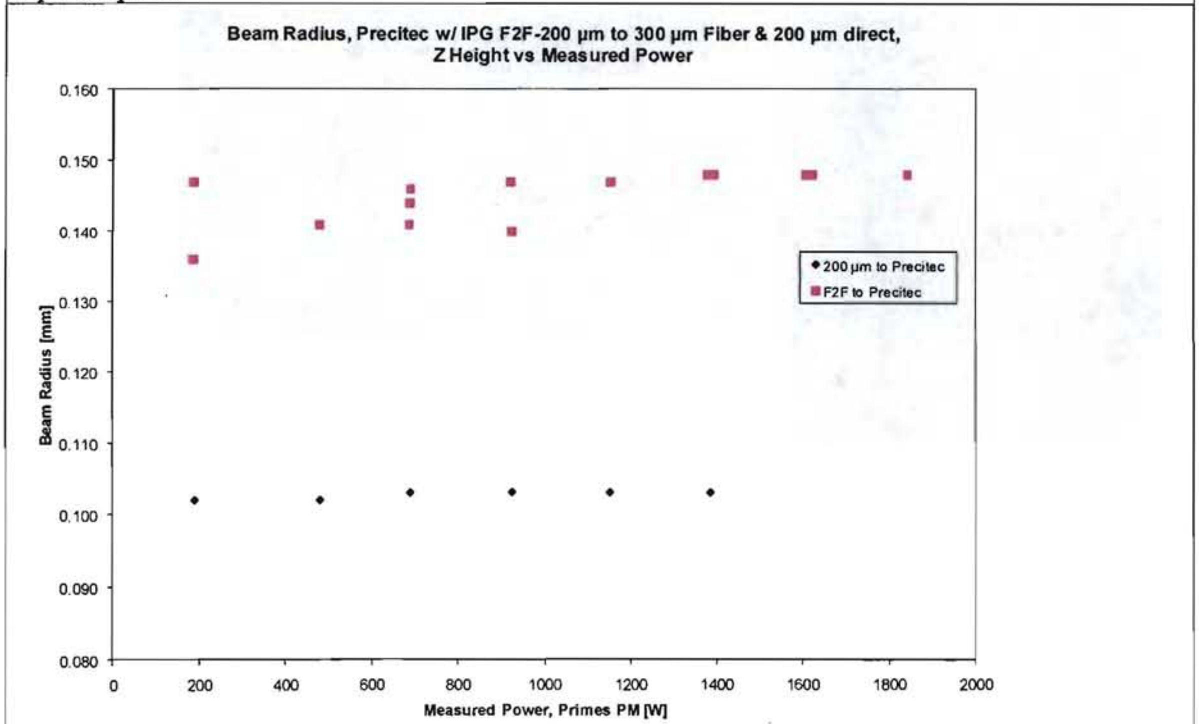


Figure 22. Second moment spot radius for two optical paths, 0.103m for the 200 micron delivery fiber and 0.147 mm for the 300 micron delivery fiber.

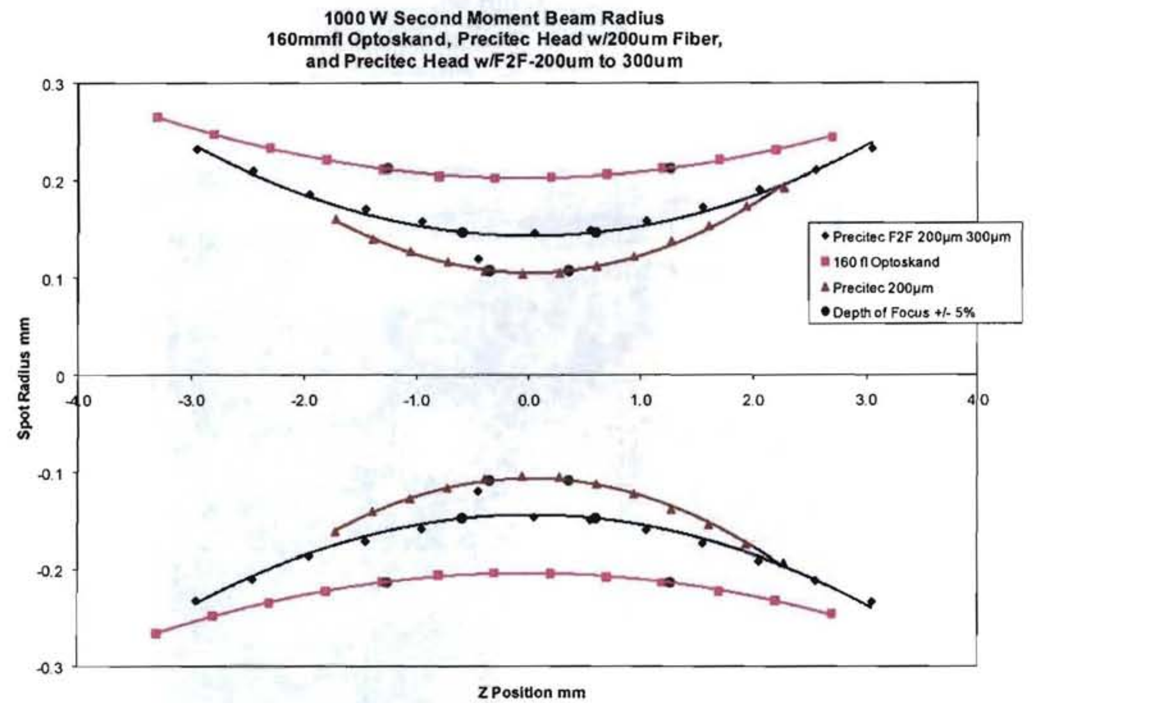


Figure 23. Second moment spot radius for three optical paths with depth of focus.

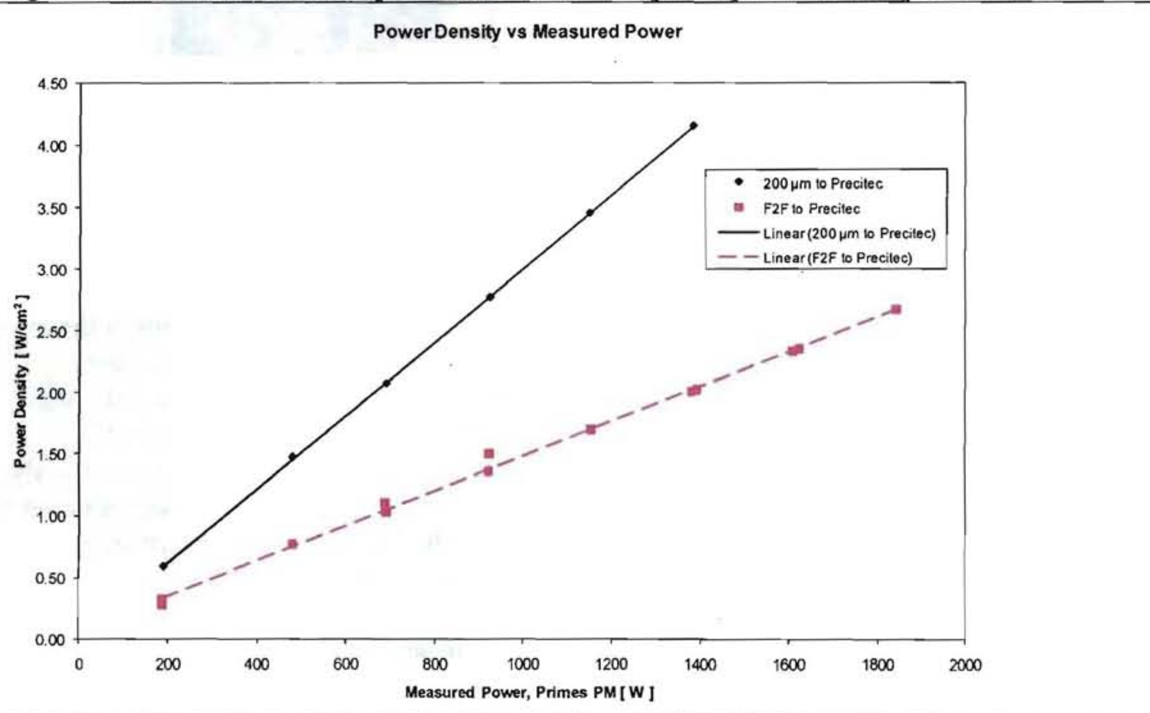


Figure 24. Power density increase for two different spot sizes and optical paths.

A comparison of the Precitec head and fiber setup with a Lumonics JK 700 series laser head and fiber optic cable is shown in Figure 25. The Lumonics head was capable of up to 400 W average power and required no cooling water and only typical optical cleaning methods.

Figure 25. Lumonics JK700 series laser head size comparison with Precitec YW-50 and IPG fiber connector.

Optical Fiber Cleaning

Optical fiber cleaning (Fig. 26) is a critical operation in the optical path setup of these multi-kilowatt lasers. We have lost multiple optical fiber attributed to inadequate cleaning technique. The fiber end must be protected at all times from dust and damage due to scratches or contact, inspected and cleaned every time it is to be installed in a beam switch, F2F coupler or laser head. The cleaning solution, swab, and method is also critical to obtaining a clean fiber and acceptable optical path. There have been a variety of methods and materials described both by IPG and the Edison Welding Institute but the method described below is the best compilation of existing practice.

1) Use isopropyl alcohol to clean exterior surfaces of optical plugs of heads before removing fiber bayonet. Do not use on the fiber ends or swabs.
2) Fixture fiber in monocular scope with illumination as shown below.
3) Remove plastic end cap and focus on front surface of quartz plug.
4) Blow off loose dust and dirt with puff of canned dry air, do not expel propellant.
5) Use clean room wipes and solvent to carefully wipe away particles.

6) Use fresh optical grade Acetone for final wipes to avoid leaving the film of alcohol. (Some recommend fresh optical methanol)
7) Focus to far side of quartz plug to inspect connection to the fiber. The black dot needs to be imaged as sharp. The outer green dot may show some glue around the periphery but that is OK.
8) IPG reps have spent up to "2 hours" cleaning a fiber. In dusty environments try setting the cleaning stage high and pointing the fiber downward to avoid catching dust after cleaning.
9) Remove plug on receptacle for fiber (head, coupler, switch) and quickly insert fiber bayonet. Use the double click twist to assure interlock contact. Be sure to confirm the correct directionality of the fiber input verses output. The output end of the IPG fibers have the spring support at the bayonet base and the strain relief coil at the input end of the fiber.
10) The metal ferrule is removed from the fiber input ends but often left on the fiber output ends to protect the quartz plug from damage during handling. This removable ferrule also has an arrow associated with input or output. These ferrules can be inadvertently switched from one end of the fiber to another, but was more of a problem with Optoskand fibers. We never got a good answer as to what technical requirement or functionality is related to the directionality of the fiber.

Figure 26. Fiber cleaning optical stage setup.

Modulation study:

The IPG laser was modulated at 50% duty cycle square wave at a frequency from 0.2 Hz to 2 kHz and power from 6kW (using all laser modules) down to 10% of one laser module. The beam was directed to the Window / Boot station. The intent was to demonstrate the robust function of the laser under extreme switching conditions at full power and to determine what frequency was required to produce a stable power reading at low single module output of 10%. Figures 27, 28 shows graphs of output power verses set power at 50% modulation. One laser module operating at 10% created a stable 40 W output at 200 Hz, was deemed sufficient for small brazing operations Fig. 29.

The IPG laser was set up in Local Mode. Referring to page 20 of the IPG manual, the pins of the Safety connector A1 (24V signal) and A2 (ground) were used to connect to a BK Precision Function Generator (connected to IPG laser analog interface input) and monitored using a Tektronics TDS 2024 digital oscilloscope. The beam was direct through Channel 2 into a PRIMES power meter. Starting Laser Net , External, ON, in local mode we started requested power of 1 kW and monitored 960 W with a power offset at the meter of 19 W. Laser emission was not achieved until the function generator was started using a square wave at a 12 V signal peak.

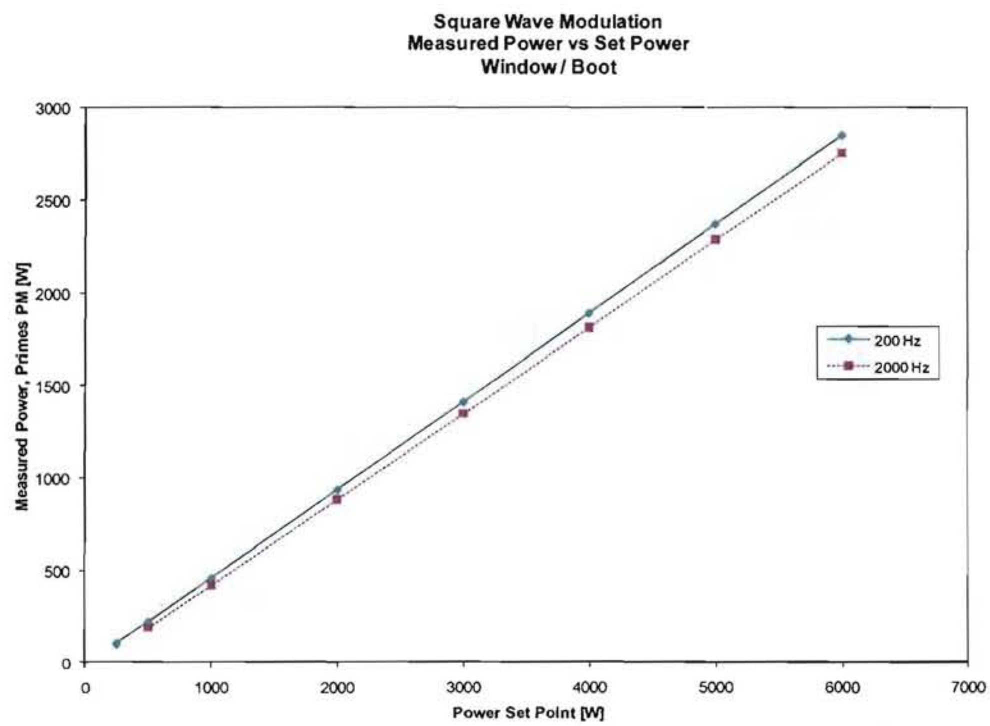


Figure 27. Modulated power increased linearly over the entire range. Approximately 3% less power was transmitted when increasing the frequency from 200 Hz to 2000 Hz.

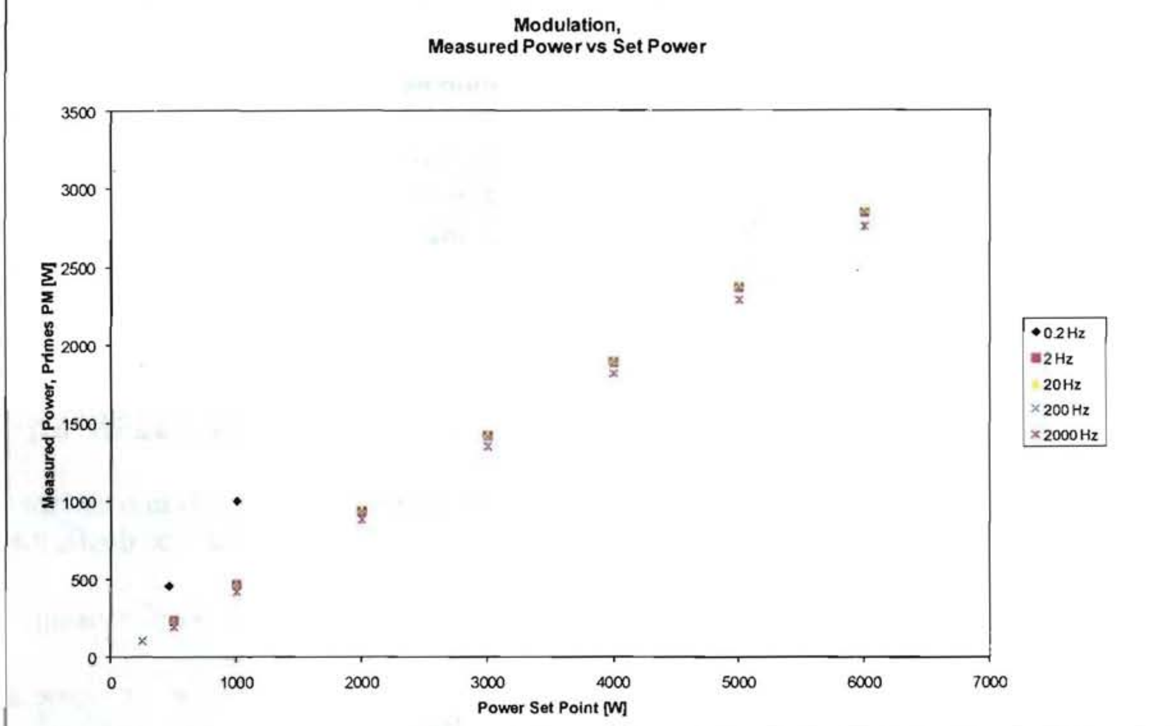


Figure 28. Power measurements were inaccurate at 0.2 Hz frequency.

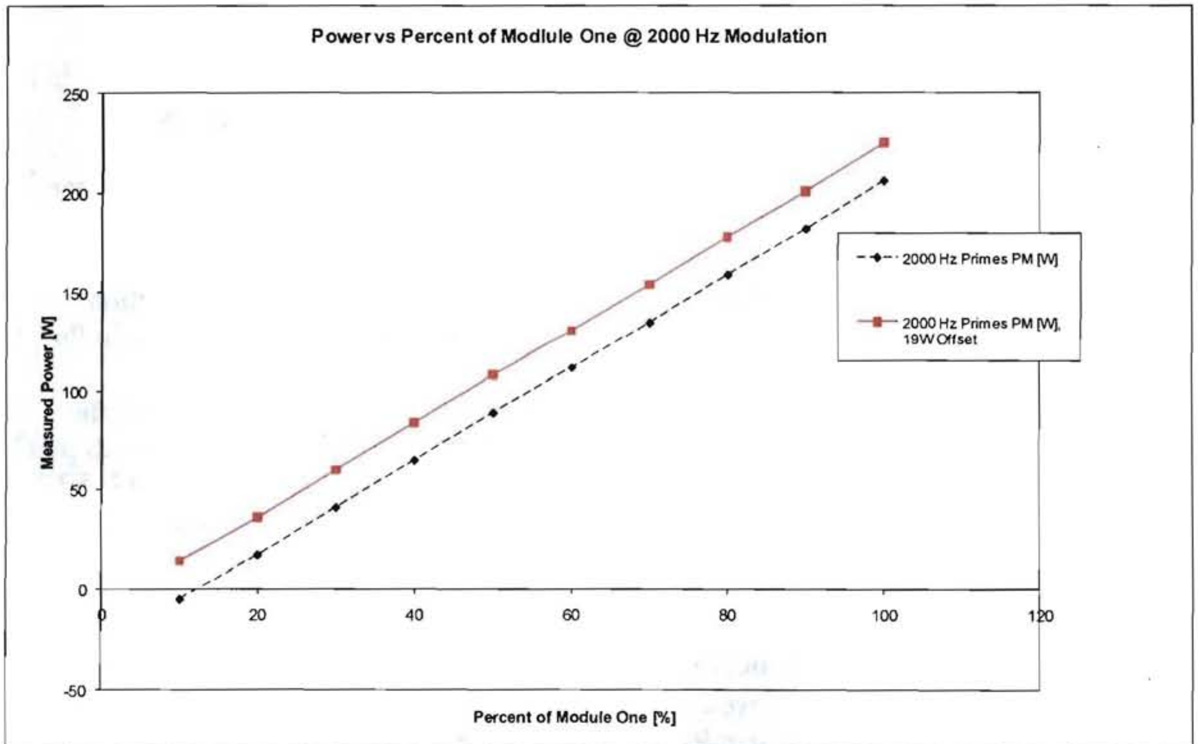


Figure 29. Power response at 50% square wave modulation was linear when reduced to 14 W measured output.

Results and Conclusions:

- Nearly every goal of the initial characterization plan was met. The Window / Boot configuration was shown to be robust.
- The IPG laser was shown to perform well over its entire range of 6kW on each of two channels 1) the window boot configuration and 2) the IPG F2F and Precitec head configuration in this initial round of testing.
- Minimum laser power loss on the order of a 2% percent was measured for the long optical paths at full power.
- Minimum temperature rise of < 3 °C was measured for the Rofin 120 mm collimator when using a 300 micron delivery fiber.
- Square wave beam modulation was demonstrated over a range from 0.2 Hz to 2 kHz at 50% duty cycle.
- Beam modulation was also demonstrated over a range of powers from 6 kW for all modules to 14 W for 10% of one module output. This demonstrated the facility to perform low power brazes as well as high power welding.
- A weld on a bar of stainless steel was demonstrated to the program office using the window boot setup.
- Laser focus spot sizes for the Precitec head with F2F connector were very close to that of EB and the LLNL IPG laser system Refs. 4-5.
- Further laser characterization, spot size measurements and burn in is planned for Q1 FY10.
- Laser verses EB weld trials are planned for Q2 FY10.

- The Laser Net software demonstrated certain short comings that would need to be resolved within the control software of a production system. Of particular concern were the indication of laser Emission OFF when it is ON and the selection of full laser power by the positioning of the cursor are the control bar without selection by clicking. Note: LANL does not rely on this indicator for laser eye safe operations.
- The IPG optical fibers require an extraordinary level of cleaning to function adequately. This level of cleaning may be difficult within the confines of a Pu glove box.
- The IPG optical fibers now have a "tension relief" coil at the input side of the fiber. This coil would have to be accommodated within the Pu glove box as part of the final fiber delivery connections (2) between the output of the two (2) F2F (fiber to fiber) connectors and the laser heads for 1) the girth welding station and 2) the tube welding station.
- The Precitec laser head is large and requires its own chilled water cooling. The size of the head may preclude the use of focal length lens over 200 mm, that may be required to avoid a fogging film on the cover lens.
- The dual girth and tube welding glove box station, as currently proposed for the Modern Laser System, would require a minimum of 16 water lines within the glove box. A significant number of signal cables associated with interlocks and monitoring will need to be routed and passed through a bulk head connection

within the globe box. The complexity and robustness of this configuration will require further assessment.

- The associated flow controls and interlocks required for the F2F connector adds a substantial level of complexity to an already long laser–interlock chain.
- The 181 control interface was not tested due to a blown fuse but is planned for Q1 FY10.

References:

1) T.J. Lienert, J.E. Bernal, "Interim Report on Optics Evaluation for Boot Assembly", 7-24-09
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3) J. Milewski, IPG Training Topics and Closeout Report, V4, August 11, 2009.
4) J. Elmer, R. Pong, Development of Fiber Laser Weld Parameters for Stainless Steel and Refractory Metals", LLNL-TR-413222, May, 2009.
5) J. Elmer, "Characterization of Defocused Electron Beams and Welds in Stainless Steel and Refractory Metals using the Enhanced Modified Faraday Cup Diagnostic", LLNL-TR-410752, February, 2009.

Appendix A:

LANL Coupler Setup

Basic fault indicators

No flow LED read out will be 0.00 could be bad flow sensor or broken/blocked line. In this view FS4 line is kinked therefore the readout is 0.00.