LA-UR- 11-06506

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Title: Characterization of a Materials Processing Laser Used for Drilling and Welding

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Intended for: FABTECH 2011

Characterization of a Materials Processing Laser
Used for Drilling and Welding

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Introduction

Characterization of the power losses, power stability, focus conditions and beam quality is essential for lasers used for materials processing. This requirement is especially important for controlling welding and drilling quality since the different processing regimes (conduction mode welding, keyhole mode welding and drilling) are differentiated by power density. LANL has recently procured a 70 W pulsed Nd:YAG laser intended for drilling and welding applications. The objective of this effort was to characterize the performance of this laser to permit fundamental insights into materials processing studies and to provide a comparative baseline for possible future changes in laser performance.

Technical Approach

The laser that was characterized is a Unitek-Miyachi LW-70A pulsed Nd:YAG laser that permits fiber delivery of the beam through two channels. The beam delivery system was comprised of a 200 μm SI fiber, 120 mm collimator and 120 mm triplet focus lens assembly with cover glass. Temporal profile measurements of the pulses were recorded with an oscilloscope. Power measurements were conducted using an Ophir L40 (150) Thermal Sensor. A modified Kapton film technique was employed to characterize the beam profiles. Beam profiles were fit to the beam propagation equation to determine measures of beam quality.

Results and Discussion

Power stability results indicated that the average power varied by no more than ± 0.25 W at higher powers (45 to 60 W) and much less at lower powers (10 W). Integration of the area of the several temporal pulse profiles indicated that pulse energy varied by no more than 1%. Total power loss through the beam delivery system ranged up to approximately 11% at higher power levels for both channels with the greatest losses occurring through the collimator and lens assembly owing to the large number of lens surfaces. Measurements of the beam size exiting the collimator suggested that the beam enters the focus lens assembly with a converging half-angle of between 6 to 7 mrad.

Initial Kapton measurements used films held in a 35 mm slide holder and were plagued by inconsistencies from flexing of the film due to use of a cover gas (to blow away burned debris) and to a recoil force during burning of the film. The extent of flexing increased with increasing distances from the edges of the film holder. In later measurements, the edges of the films were taped to a cover glass made of optical quality fused silica. For these measurements, the standard deviation for groups of six beam diameter measurements made at the same focus position was less than 0.0005".

The focused beam radius determined for the 120 mm focus lens assembly was 0.0073". The M^2 value for this data was 120.2 and the beam product parameter (BPP) was 22.6 mm·mrad. This BPP value was much larger that the estimated value calculated for the laser cavity, but was identical to that for the beam exiting the fiber. The position of the minimum beam radius varied slightly when a cover glass was used in the focus lens holder.

Conclusions

The findings of this work proved useful in determining the average power density incident on the sample surface for welding and drilling trials and the position of the minimum beam waist for drilling trials undertaken in a companion study to be presented at the same conference. The results of this work also allowed direct comparison of the performance of a nominally identical laser system at another DOE site. The modified Kapton film technique developed here gave repeatable and accurate results. The BPP for the focused beam profile of a fiber delivered laser is determined by the BPP exiting the fiber.

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- Objectives.
- Experimental Approach.
- Pulse Energy Repeatability.
- Power Losses Through the Optical Train.
- Beam Spatial Profiles Using Kapton Film.
- Beam Spatial Profiles Using Beam Profiler.
- Discussion
- Conclusions/Summary.

Introduction

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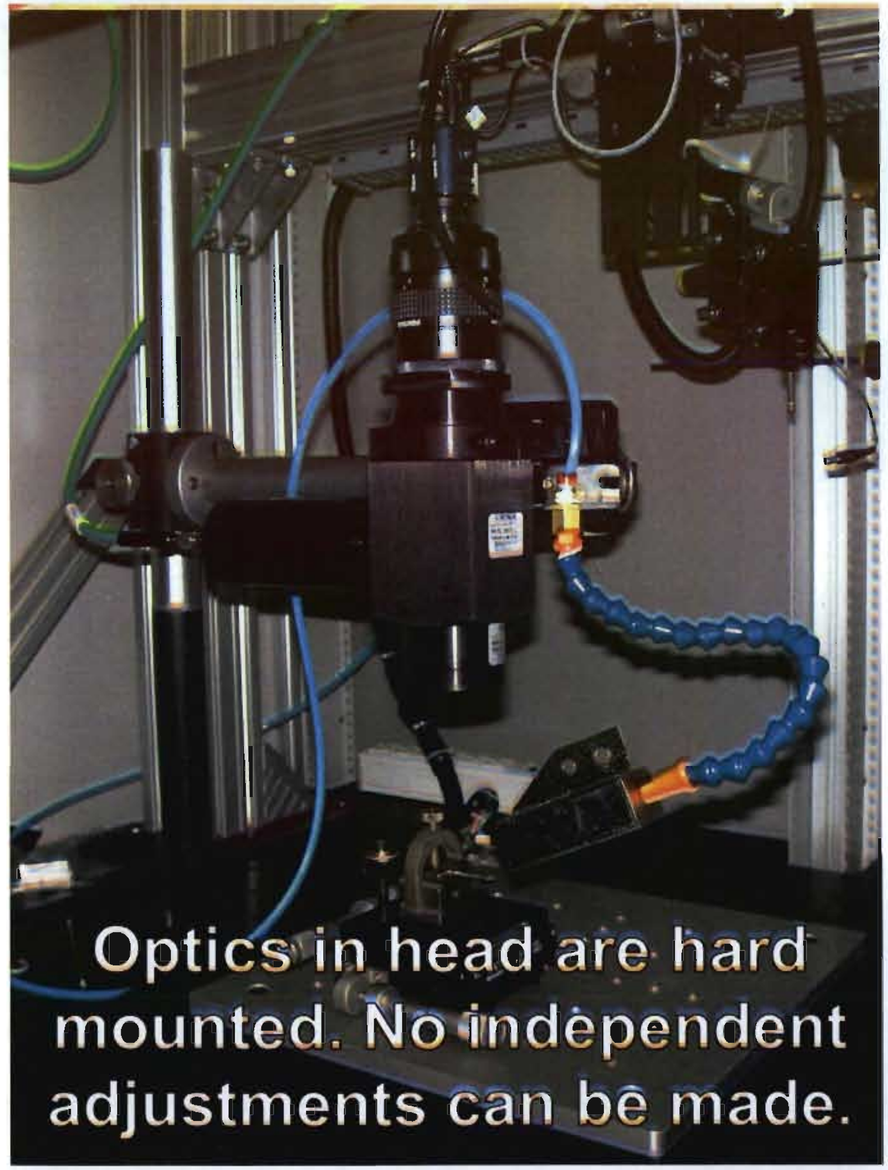
- LANL has recently procured a 70 W pulsed Nd:YAG laser intended for drilling and welding applications.
- The objective of this effort was to characterize the performance of this laser to permit fundamental insights into materials processing studies and to provide a comparative baseline for possible future operating issues.

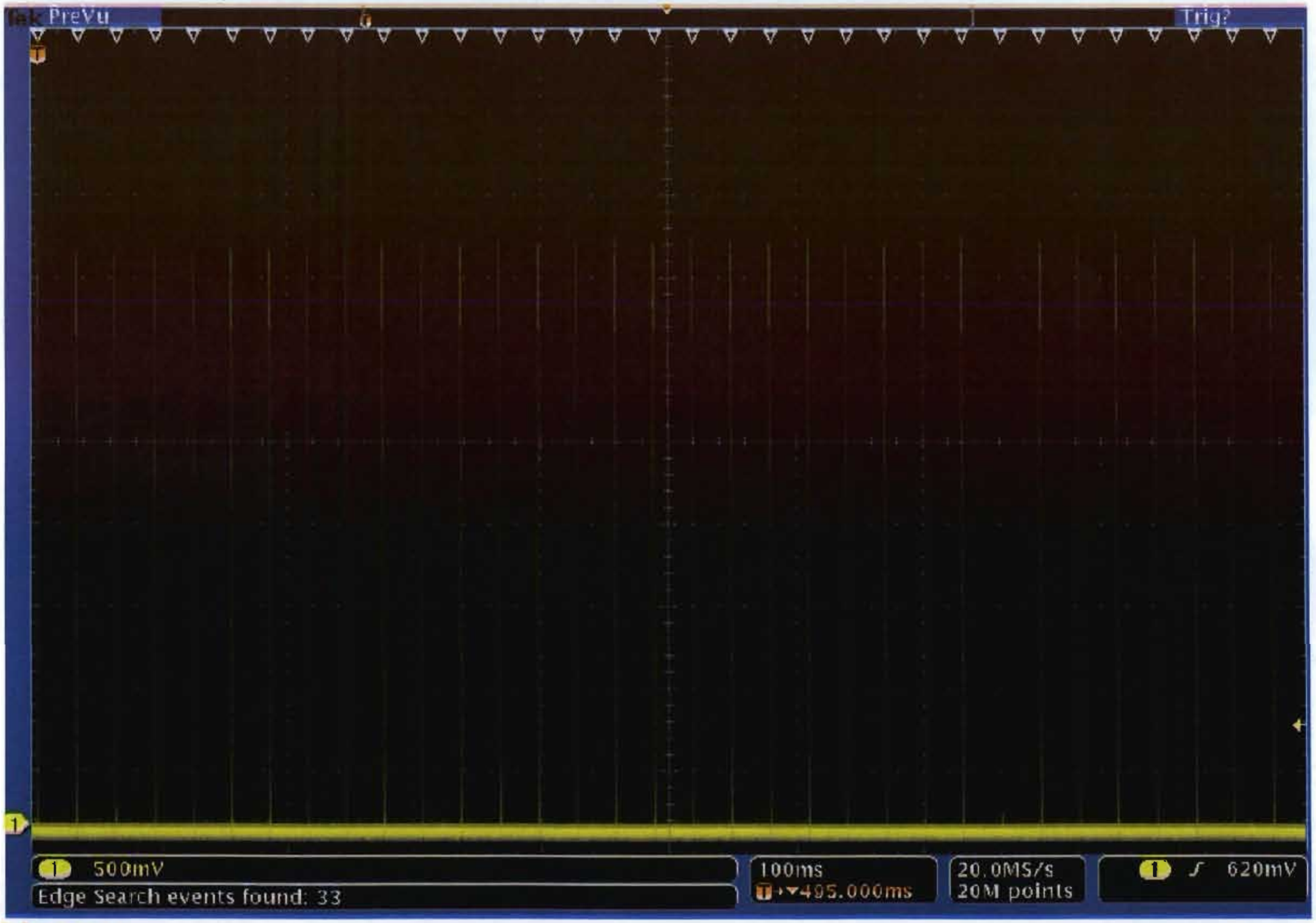
Experimental Approach

- Unitek-Miyachi LW-70A pulsed Nd:YAG laser that permits fiber delivery of the beam through two channels.
- 200 μm SI fiber, 120 mm collimator and 120 mm triplet focus lens assembly with cover glass.
- Energy and power measurements using Ophir Vega meter
- Beam profiling with 0.002" Kapton H films (using a modified technique) and Ophir-Spiricon LBS system with BeamGage software. Compare profile results for the two techniques.
- Fit beam profiles to determine minimum beam diameter ($2w_0$) and a measure of beam quality (M^2).

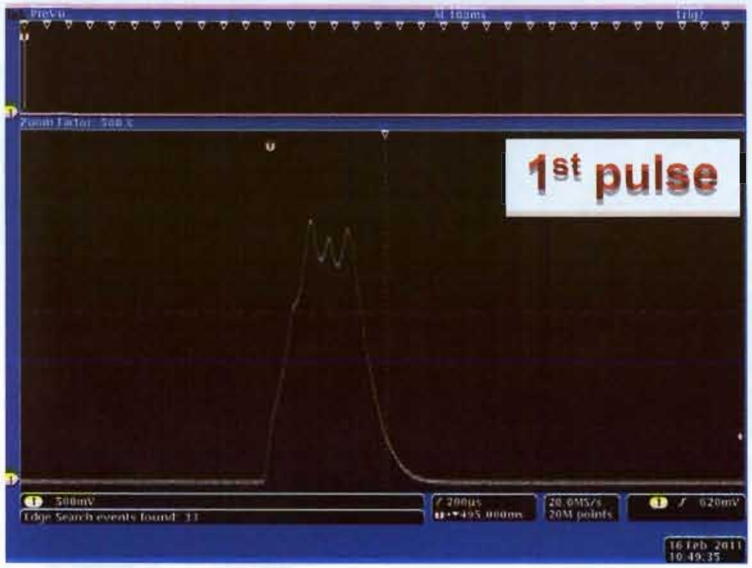
Laser and Focus Head

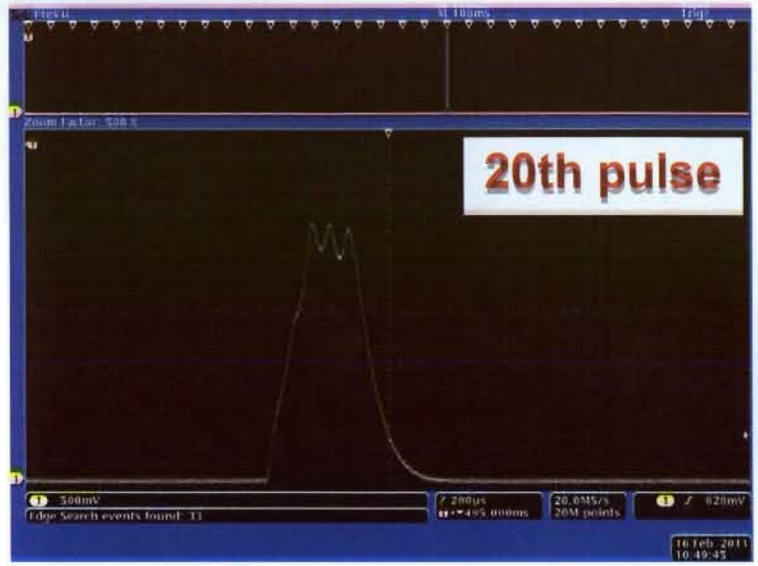


Drilling Schedule-Trial 1

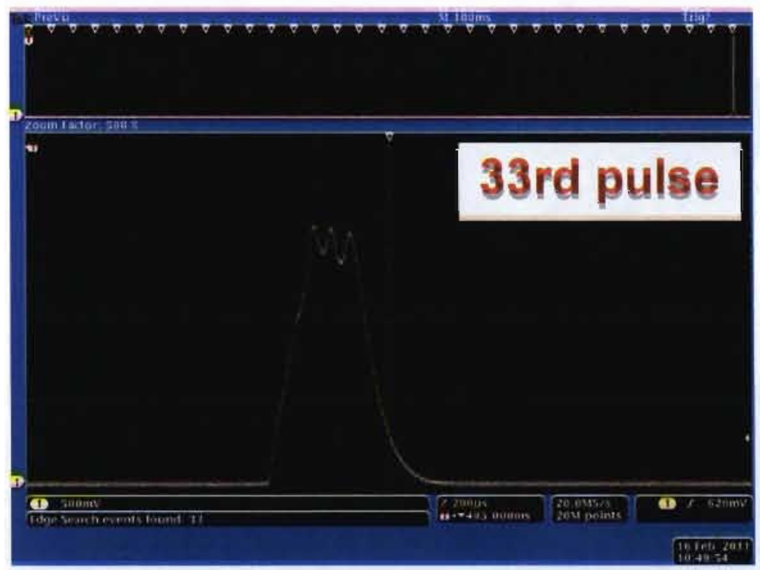


Drilling Schedule-Trial 1

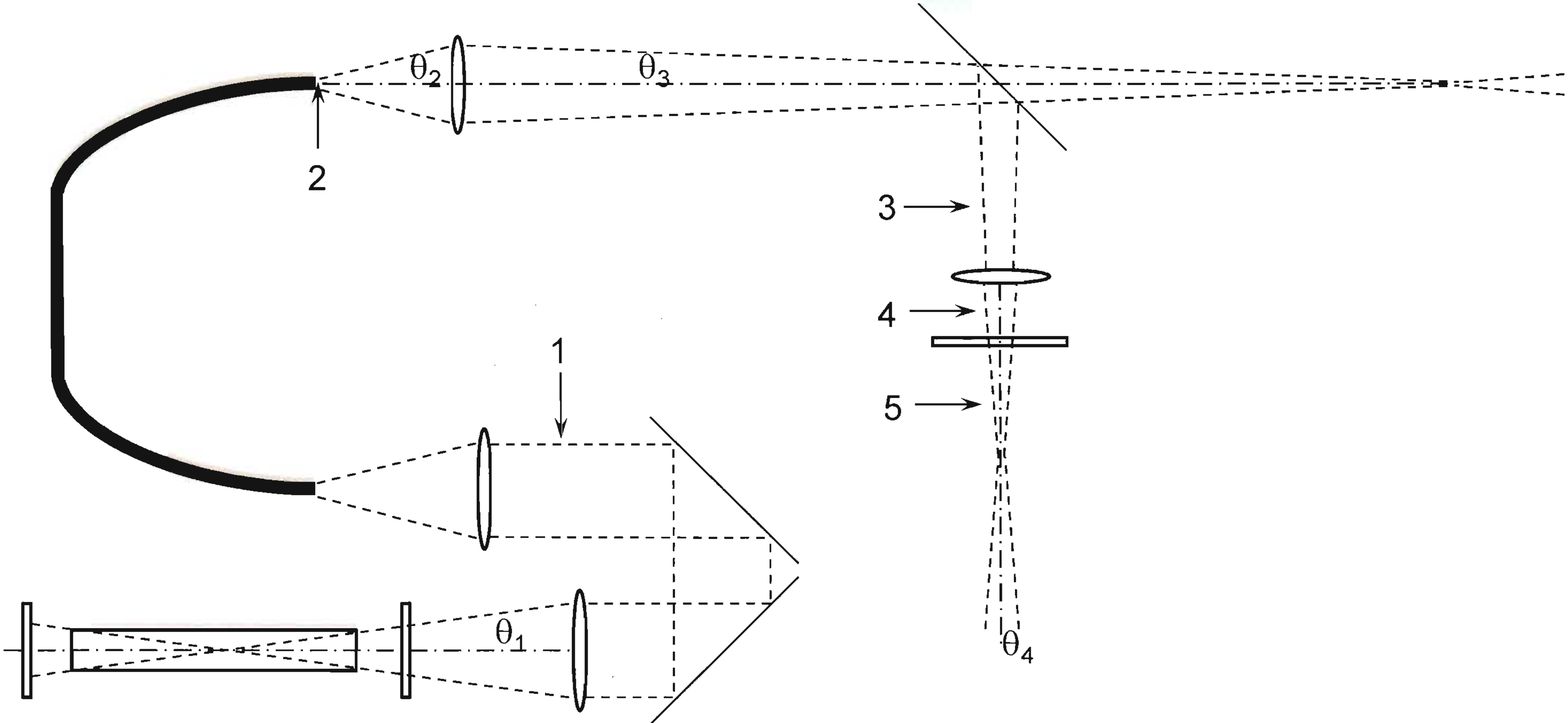




- Integration of the V vs. t signal from the o-scope for many pulses using a rect-angle method indicates pulse energy variations of $\leq$1%.

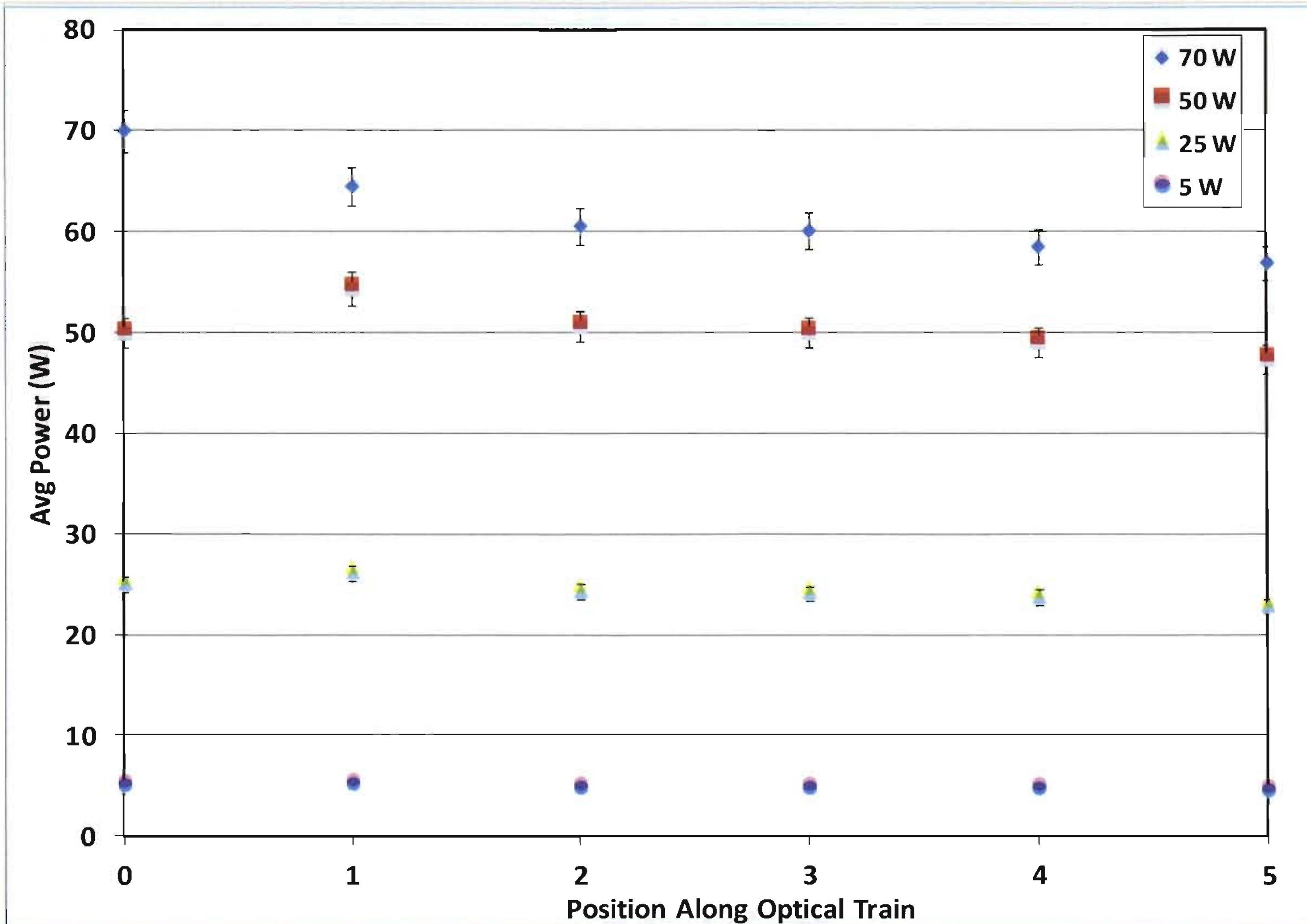


Power Losses Through Optical Train



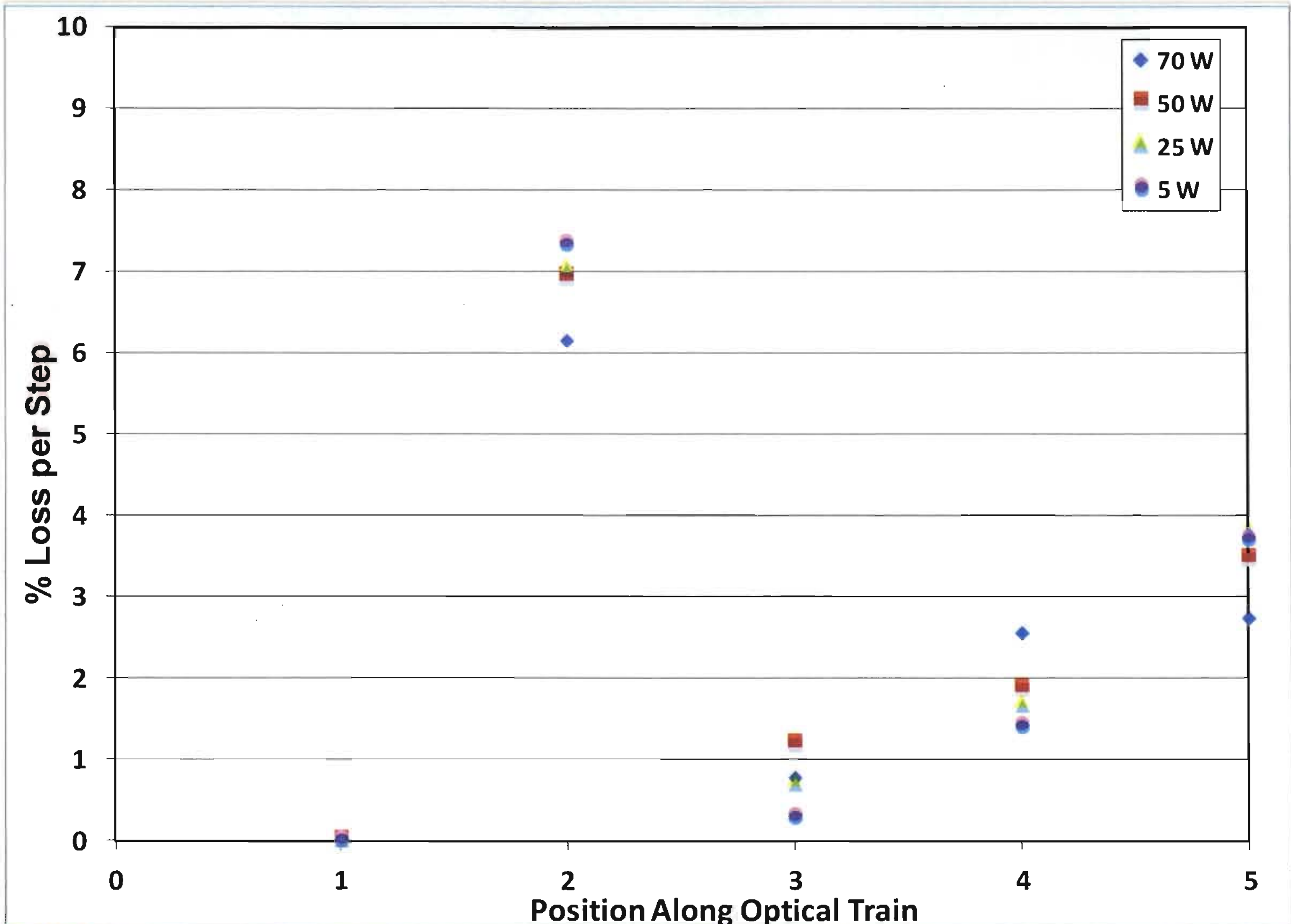
Position#	Location
0	Power Requested from Laser
1	Before Launch
2	After Fiber
3	Head w/o FL
4	Head w/FL, No CG
5	w/ non AR CG

Power Losses Through Optical Train



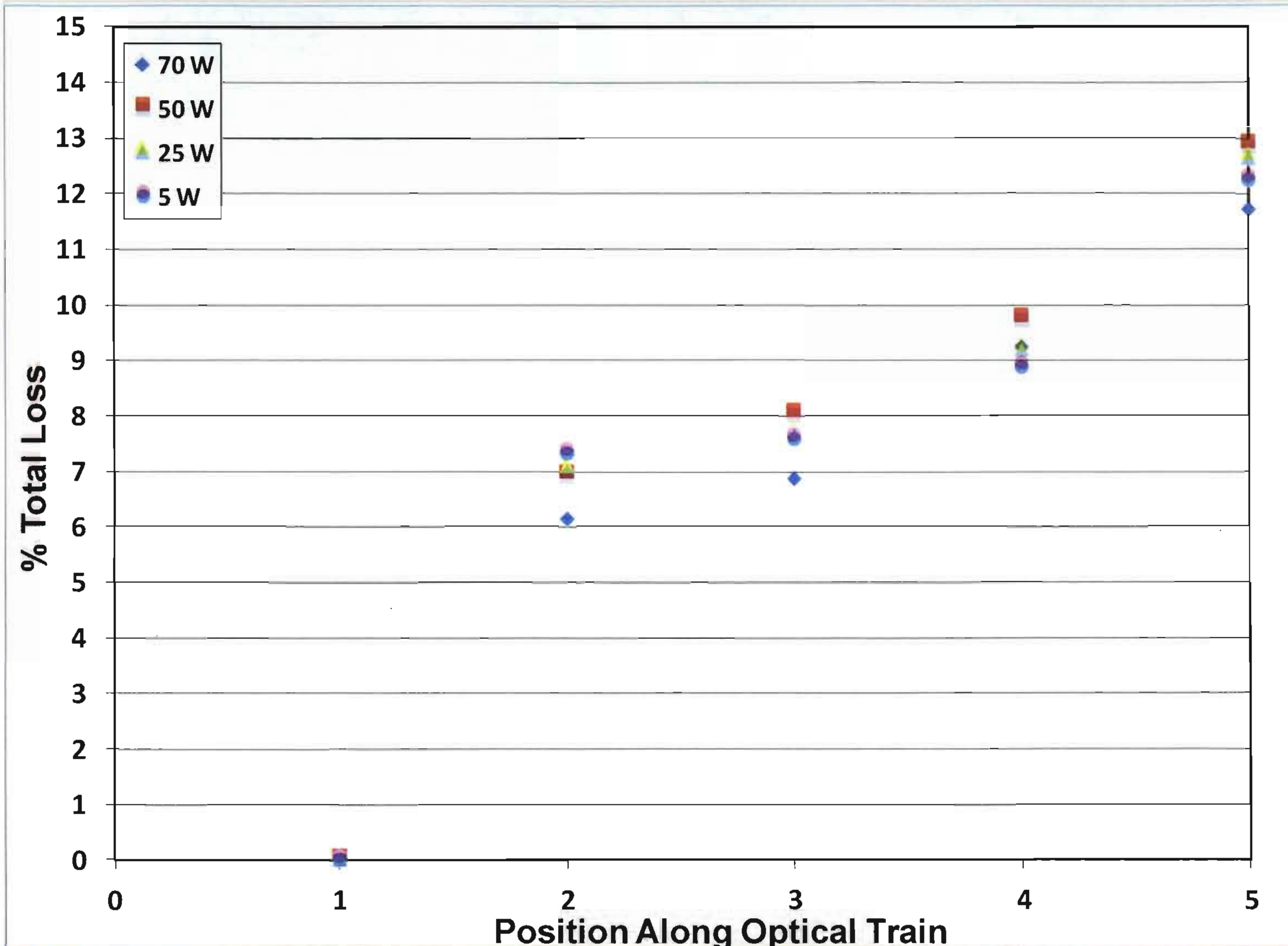
Power vs. Position

Power Losses Through Optical Train



% Power Loss per Step vs. Position

Power Losses Through Optical Train



% Total Power Loss vs. Position

Kapton Beam Profiling

- Kapton is a polyimide film that has been used extensively for profiling of laser beams. There are at least a dozen types of Kapton.
- The films were initially held in a snap-together 35 mm slide holder while irradiated by the beam.
- Early profiling studies used Kapton HN films that contain calcium phosphate dibasic ($CaHPO_4$) as a slip additive. Repeatability issues with the HN films prompted us to move to Kapton H films.
- Initial profiling studies using the H films were also plagued with repeatability issues until flexing due to the recoil force during burning was discovered.

Kapton Beam Profiling

- Subsequent work type taped down edges of type H films to optically flat windows to provide support and eliminate flexing. This process gave a standard deviation for sets of 6 burns made at the same focus position of < 0.0005".
- Dimensions of the major and minor axes of burn holes were measured at 20x using an optical comparator.
- Burn diameters were plotted vs. z position, and the data was fit to the beam propagation equation to determine to determine minimum beam diameter ($2w_0$) and a measure of beam quality (M^2).

Kapton Beam Profiling

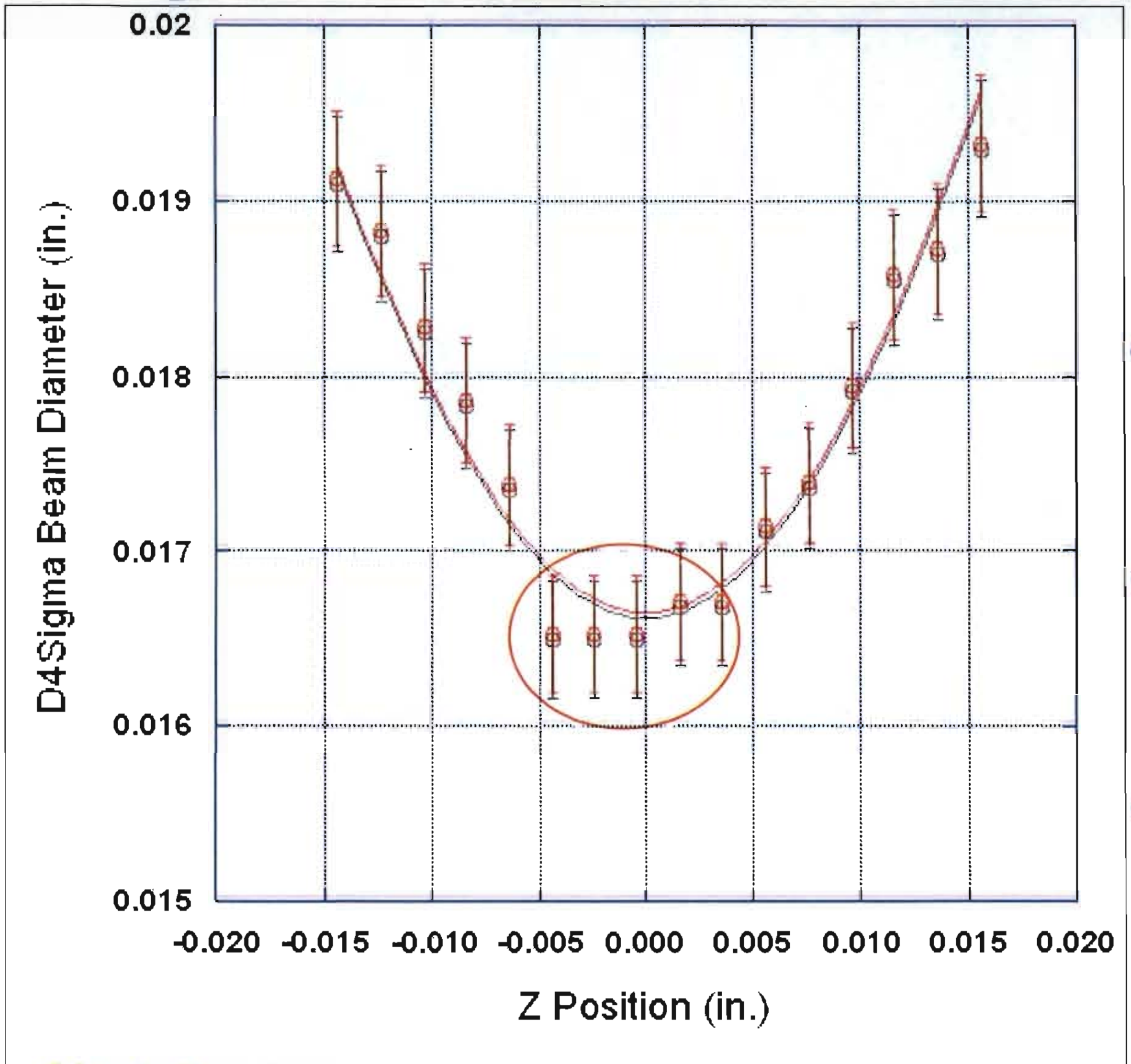
- The beam propagation equation is:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z\lambda M^2}{\pi w_0^2}\right)^2}$$

where w_0 is the minimum beam radius and M^2 is a measure of beam quality.

- This relationship is essentially the equation of a hyperbola that maps the caustic presentation of the beam profile.
- Fitting was done using the fitting software in Kaliedagraph by iteration using initial estimates provided by the user.

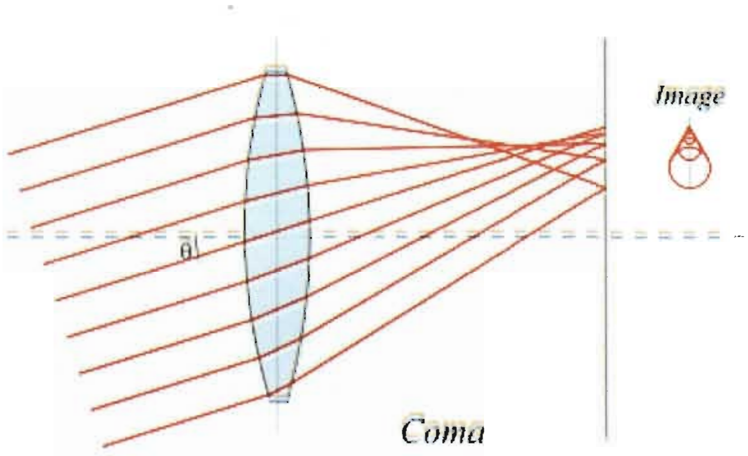
Kapton Beam Profiling

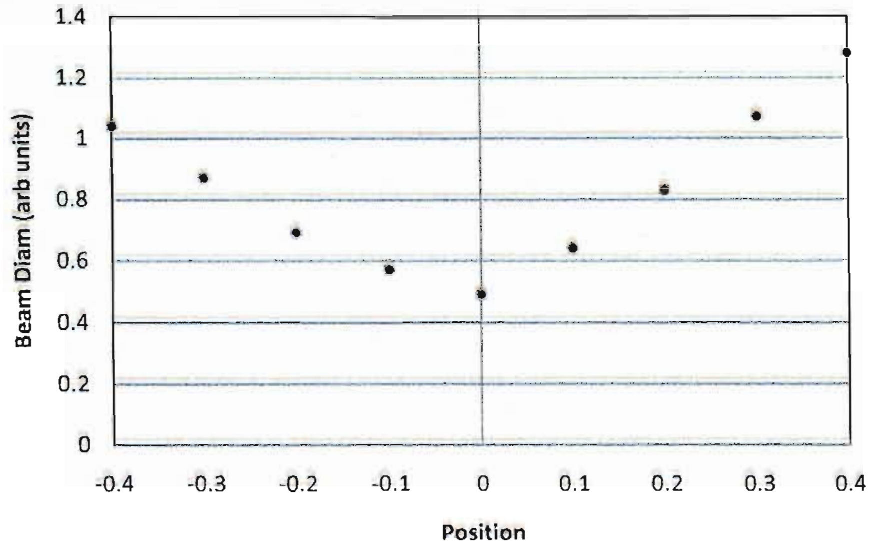


y = m1*sqrt(1+(m0*m2*.001064...		
	Value	Error
m1	0.016619	8.4099e-5
m2	32.685	0.84954
Chisq	6.6855e-7	NA
R^2	0.95478	NA

- Fitting assumes that the caustic is sym-metric about z=0.
- The fitting parameters indicate that $2w_0 \approx$ 0.0166" and $M^2 \approx 32.7$.
- Note the poorer fit on the –ve side of the minima=> coma due to misalignment?

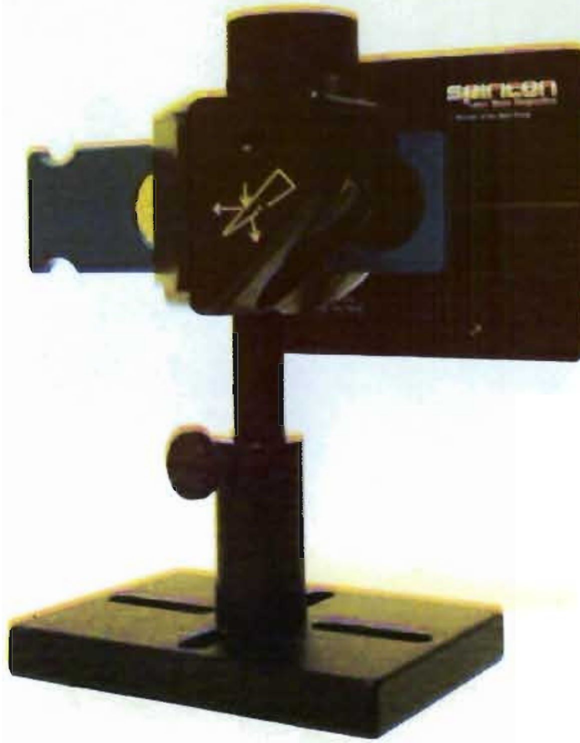
Optical Coma

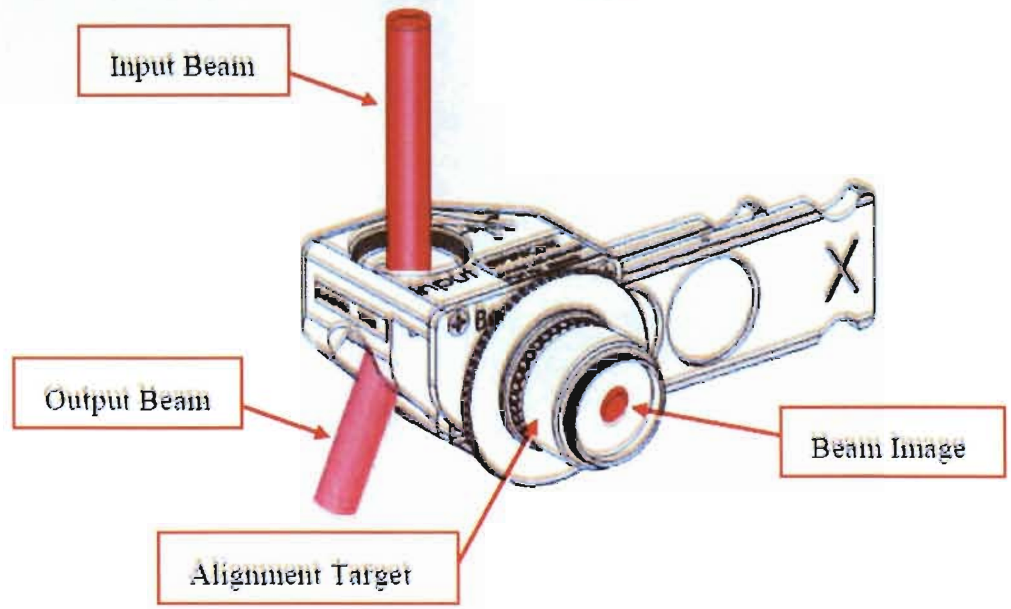




- **Coma is a first-order aberration that occurs when the beam axis and axis of the optic are misaligned by an angle θ.**
- **Coma gives an image that is shaped like a comet. It can result in a caustic profile that is not symmetric about z = 0.**
- **If the minima of the fit in the previous slide is forced to go through one of the data points in the oval, the caustic profile is not symmetric about z = 0 (similar to that above).**

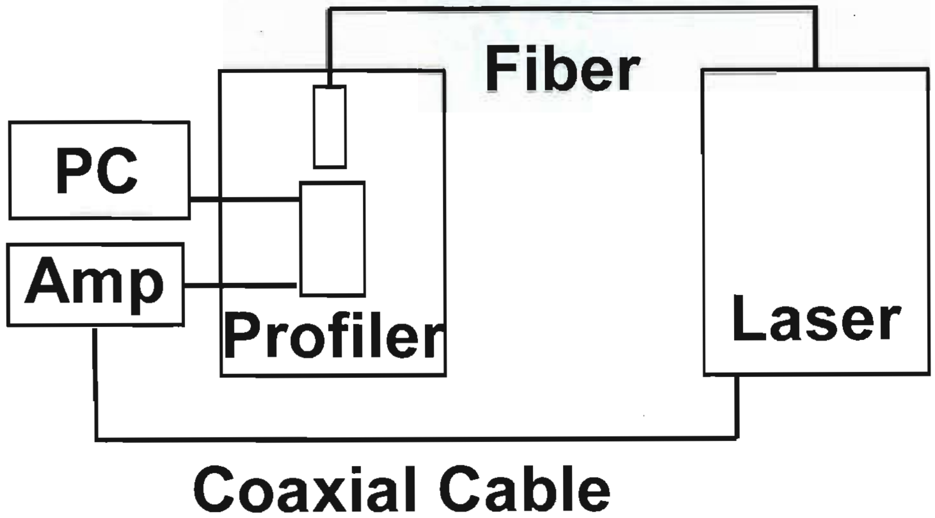
Ophir-Spiricon LBS-300 System





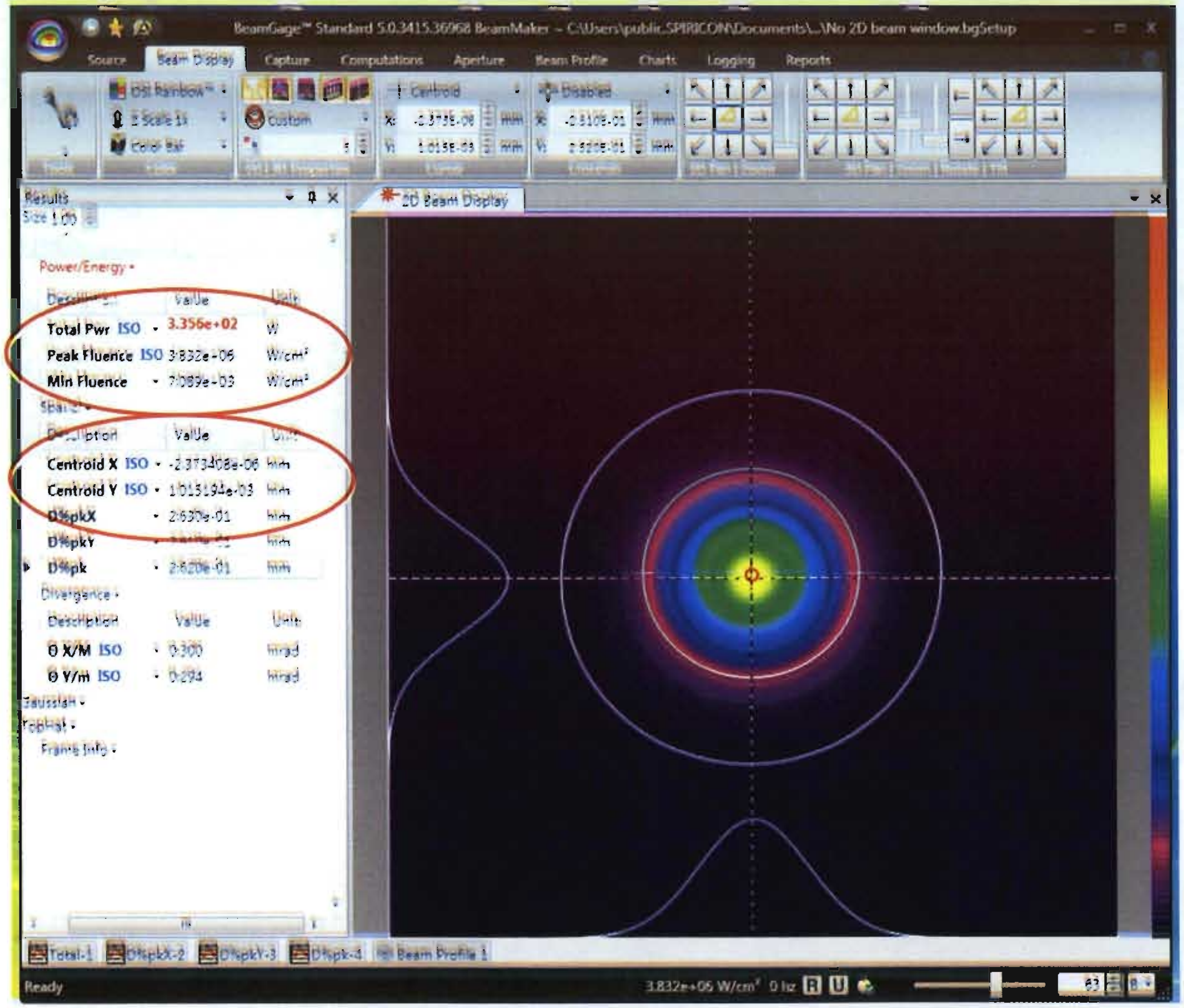
- This system is very capable but is tricky to use. Good news/bad news.
- The optical axis of the system must be closely aligned to the beam axis for useful results.

Beam Profiler Results



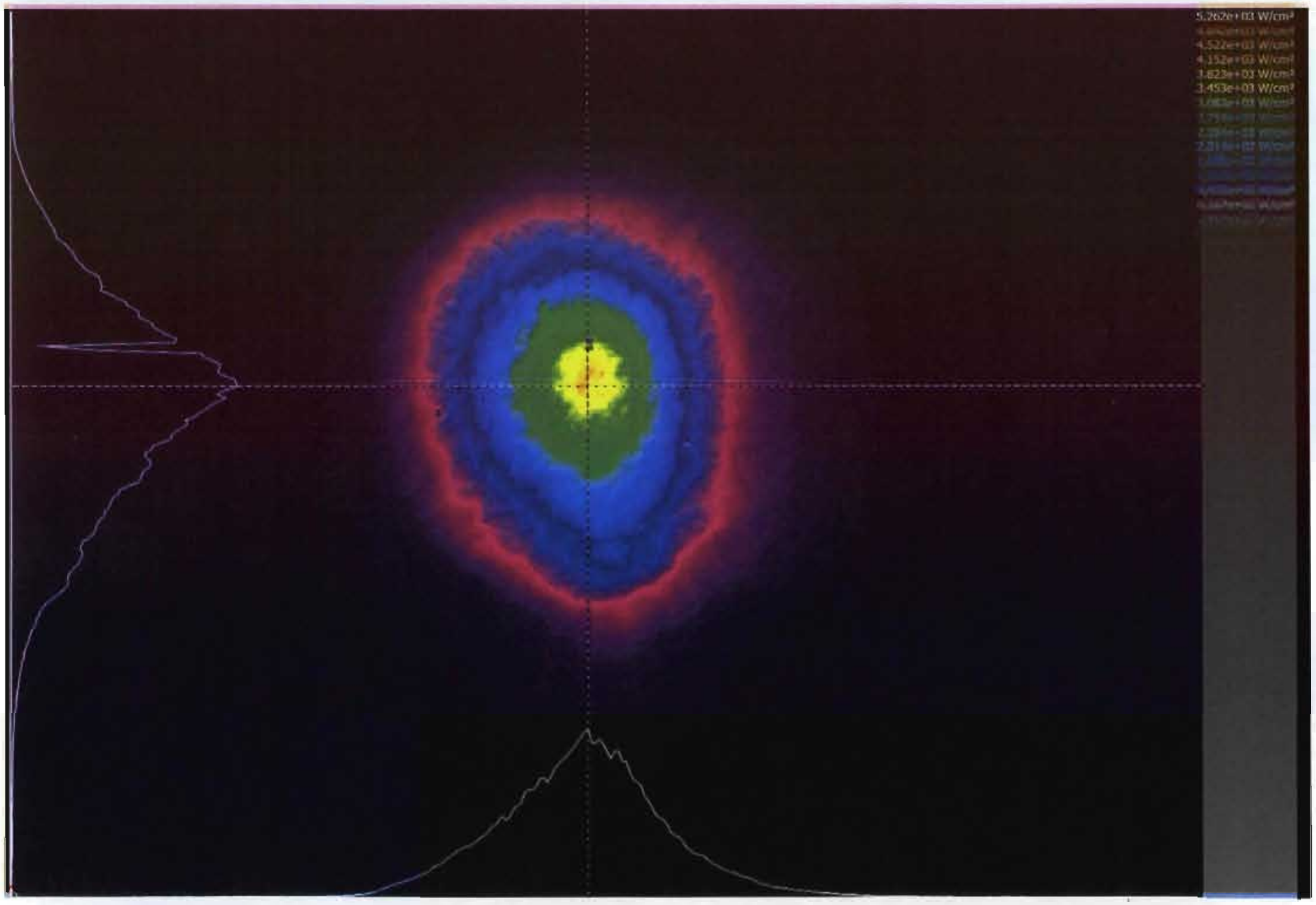
- We had difficulty in getting the profiler to trigger directly from the laser 0 to 5 V TTL output. The problem was solved by amplifying the TTL signal.
- The trigger level is 3.5 V. The trigger delay was set to capture the profile at the second maxima of the temporal pulse profile.

Typical Screen Shot of Software



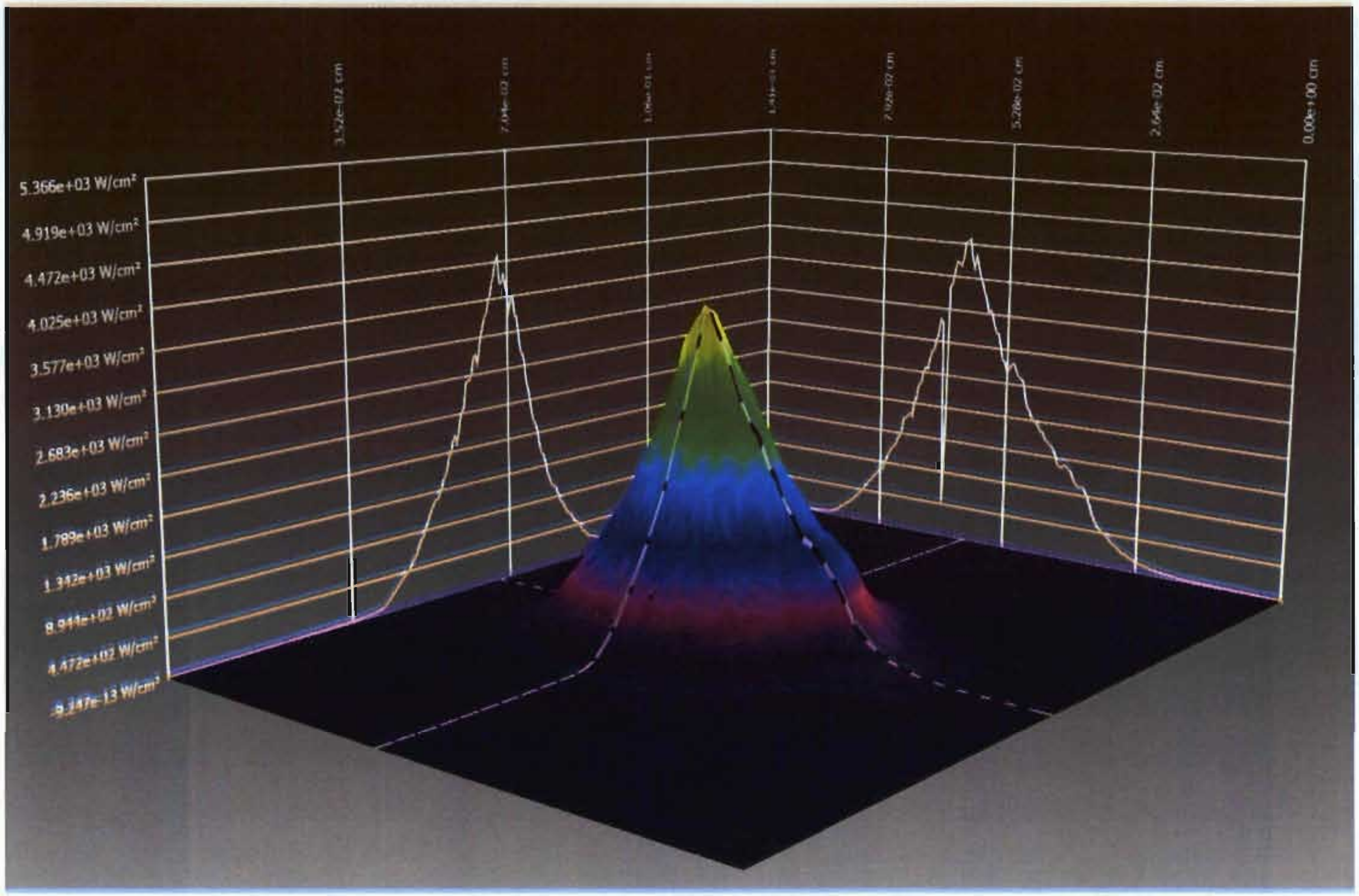
- Data not from current measurements.

2D Presentation



- Measurement near minimum waist.
- Note comet shape (confirms coma?)

3D Presentation



- **Measurement near minimum waist.**

D4σ or Second Moment Width

- **D4σ is shorthand for the diameter that is 4 x σ (±2σ), where σ is the standard deviation of the marginal distribution.**
- **Mathematically, the D4σ beam width in the x-dimension for the beam profile *I*(*x*,*y*) is given by:**

$$D4\sigma = 4\sigma = 4\sqrt{\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)(x-\overline{x})^2\,dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\,dxdy}}$$

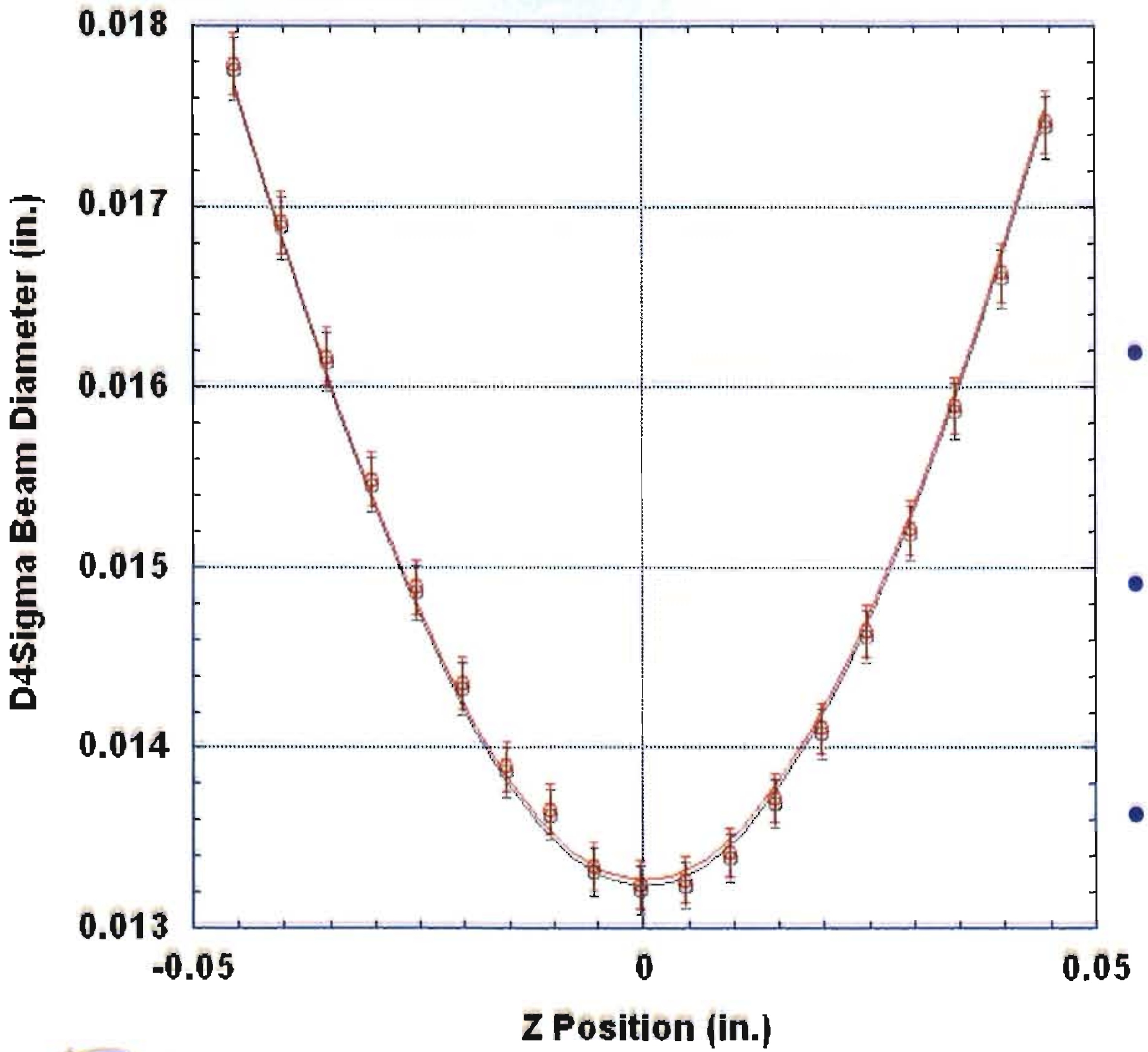
where $\overline{x}$ is the centroid of the beam profile in the x direction:

$$\overline{x} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\,x\,dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\,dxdy}$$

D4σ or Second Moment Width

- The D4σ is the ISO international standard definition for beam width for multi-mode beams. It is analogous to the $1/e^2$ diameter for a Gaussian beam.
- The wings of the beam profile influence the D4σ value more than the center of the beam profile since the wings of the marginal distribution are weighted by the square of its distance, x^2, from the center of the beam.
- Therefore, baseline subtraction is necessary for accurate D4σ measurements (performed in software).

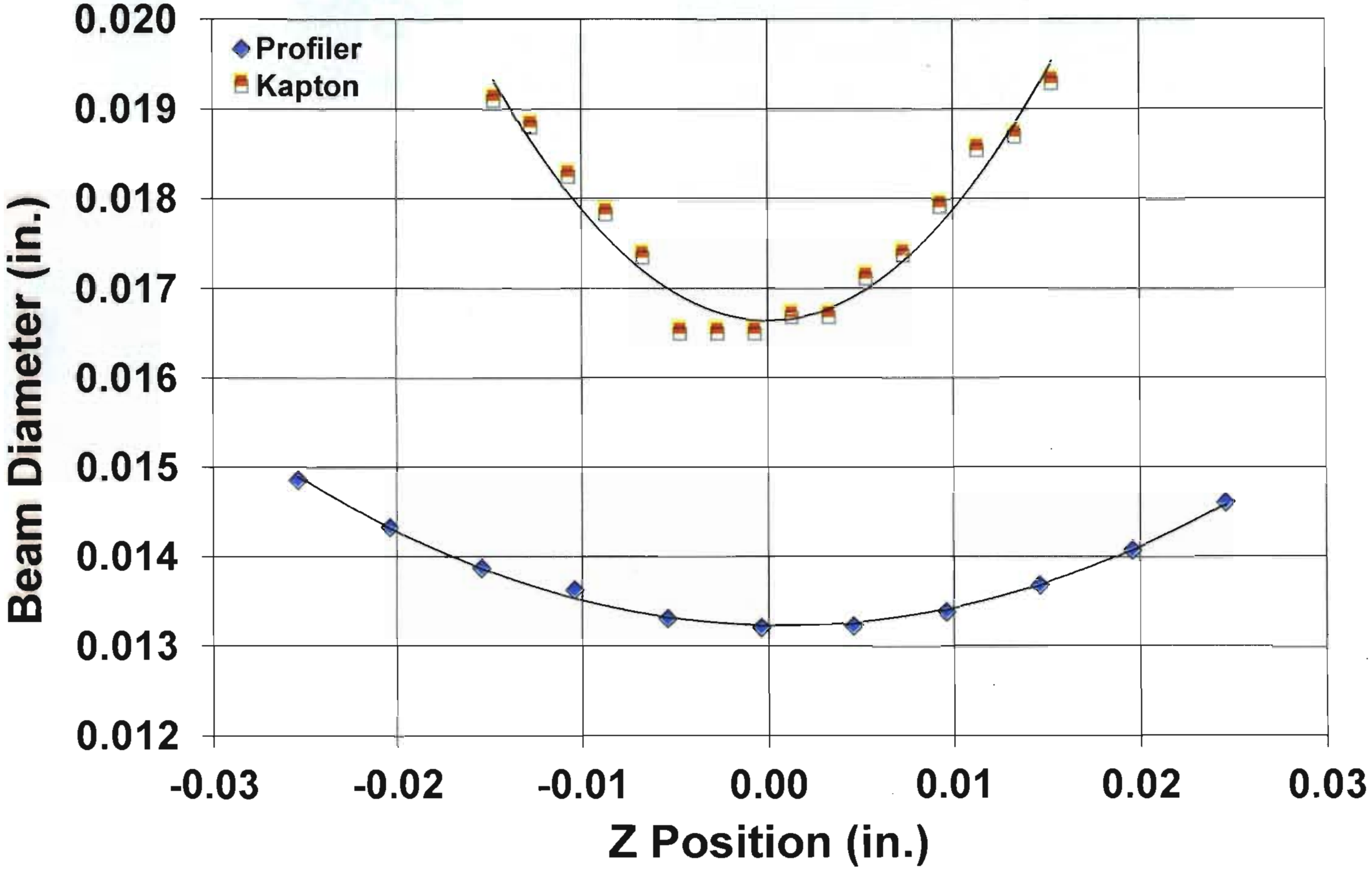
Profiler Data



y = m1*sqrt(1+(m0*m2*.001064...		
	Value	Error
m1	0.013232	2.9922e-5
m2	10.063	0.053893
Chisq	1.1617e-7	NA
R^2	0.99709	NA

- Fitting assumes that the caustic is symmetric about z=0.
- The fitting parameters indicate that $2w_0 \approx$ 0.0132" and $M^2 \approx 10.0$.
- Note the very good but slightly assymetric fit => coma due to misalignment?

Comparison: Kapton vs. Profiler



- Note that Kapton gives a larger $2w_0$ and has different curvature relative to the profiler.

Discussion

- Fuerschbach and co-workers have reported that Kapton results give the ~99% beam diameter, while the D4σ results from the profiler give something like the $1\text{-}1/e^2 \approx 86.5\%$ diameter *for single mode beams with Gaussian distributions*.
- They also gave an equation that relates the 86.5% diameter to the 99% diameter: $2w_{86.5}/2w_{99} = 0.66$.
- Using the data from this work: $0.0132/0.0166 \approx 0.796$.
- The deviation from the ideal ratio may be rationalized (at least in part) by the fact that the beam for this work is multi-mode and is not Gaussian.
- Nevertheless, Kapton studies are simpler and provide useful information for quality control in production.

Discussion

- Laser physicist have long known that the non-linear material properties of Kapton limit its utility for acc- urate beam profiling. We believe that these properties may influence the curvature of the Kapton plot. Further work is required to reconcile this behavior.
- Another issue deals with the sensitivity of the 0.002" thick Kapton film to minor changes in power density near the minimum waist. Is the sensitivity of the Kapton method described on the order of the film thickness? Additional work is required.
- Finally, the new Kapton method does not allow burn- ing of the film from both sides (as when the film is not supported). Does this influence the results?

Conclusions/Summary

- Pulse energies varied < 1% (for a given pulse train).
- The stability of average power measurements over a period of several weeks (data not shown) was < 2%.
- The greatest loss of average power occurred through the launch optics and fiber (6%-7%) followed by the non-AR cover glass (3%-4%).
- Total power loss through the optical train was ≈ 12%-13%.
- A new Kapton profiling method was developed to eliminate flexing of the film due to the recoil force.
- The Kapton profiling method results gave values for $2w_0 \approx 0.0166"$ and $M^2 \approx 32.7$.

Conclusions/Summary

- Kapton results suggested the presence of coma due to misalignment.
- The shape of the 2D profiles taken using the profiler were consistent with the presence of coma. The profiler results gave values for $2w_0 \approx 0.0132''$ and $M^2 \approx 10.0$.
- Little can be done to correct for coma since the optics in the head are hard mounted.
- The ratio for the 86.5% diameter to the 99% dia-meter deviated from the ideal value most likely because the beam used for this work was multi-mode and was not Gaussian.