Behavior of Fused Silica Under 193 nm Irradiation

International SEMATECH
Technology Transfer # 00073974A-TR

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July 25, 2000

Abstract: This report from the Optical Materials Characterization and Development project (LITG201) describes a study of characteristics of fused silica for use as lenses in exposure equipment. Samples from eight suppliers were subjected to tens of billions of exposures of a 139 nm excimer laser at various fluences to determine scaling laws for low fluence exposures. At 14 billion exposures, samples exhibited varying behavior. Some samples showed densification; some showed rarefaction. No clear trends were observed at 14 billion exposures.

Keywords: Deep Ultraviolet Lithography, Excimer Lasers, Lenses, Lithography Equipment, Materials Characterization, Optical Materials

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Acknowledgements

Thanks to the suppliers for providing samples and for their many scientific consultations. They shall remain nameless by choice at this time.

I also thank Dr. Richard Morton, Dr. Zsolt Bor, and Todd Embry of Cymer Inc. Their help in running the tests, making endless measurements and providing insight to optical behavior has been invaluable.

Thanks also to Dr. Mordechai Rothschild and Dr. Vladimir Liberman at MIT/LL. They conducted the original testing on fused silica, and have provided invaluable consultations throughout this experiment.

1 EXECUTIVE SUMMARY

Introduction of 193 nm lithography requires the use of fused silica for lenses used in wafer exposure equipment because most commonly used optical materials have excessive absorbance at 193 nm. To ascertain the characteristics of fused silica under 193 nm irradiation, International SEMATECH initiated a program to test samples from various suppliers and to determine their suitability for 193 nm exposure lenses. Initial work involved conducting tests at fluences higher than would be experienced in an exposure lens; the results were extrapolated to show that a number of the fused silica grades would indeed withstand the irradiation dose of a normal ten-year life. That lifetime dose is expected to be 50 to 100 billion pulses at a fluence of 0.1 mj/cm^2.

Samples from eight suppliers were then subjected to 193 nm irradiation to simulate the lifetime dose of a wafer exposure lens. The exposing source was a 193 nm ArF pulse train at 8 kHz. After 40 billion pulses, many of the samples exhibited rarefaction (i.e., a negative densification) that had not been previously reported in the literature.

Lens designers and tool manufacturers were consulted to determine the effect of rarefaction on imaging quality. Because the tool manufacturers stated that they needed scaling data to accurately assess the effect on imaging quality of the lens, the marathon test was suspended and changed to a scaling law test. The scaling law test was designed so that each sample was irradiated by four laser beams of different fluences. Six samples from five sources were identified, and the test was started. Measurements of birefringence and wavefront distortion were made at 2 billion pulse intervals. At 14 billion pulses, there was considerable variation among the samples. Two of the samples showed a strong densification trend, two showed a strong rarefaction trend, and two showed weaker trends that are somewhat uncertain.

The test will be continued to 25 billion pulses, which should provide clear trends to allow a scaling law determination.

2 MARATHON TEST

2.1 Test Facility

A high pulse rate exposure facility was designed and built by Cymer Inc. using a 2 kHz line ArF excimer laser. A 4X pulse multiplier was constructed of beam splitters, spatial optical delays, and beam combiners. This produced four pulses for each input laser pulse for an output pulse rate of 8 kHz. This high pulse repetition rate allowed the exposure of tens of billions of pulses in a few months. The samples were contained in a nitrogen-purged environment during exposure.

2.2 Marathon Test

The marathon test was designed to irradiate the samples with a nominal fluence of 0.1 mj/cm^2 per pulse for a count of 50 billion pulses. A sample size of 20 mm × 40 mm × 80 mm was chosen to be consistent with previous tests. Exposure was along the 80 mm axis. Samples were requested from all major suppliers of fused silica to the semiconductor exposure tool industry. The material requested was to be production grade material as supplied to the industry for 193 nm lenses. These material samples were representative of fused silica material expected to last the life of the lens. The suppliers were not asked to supply the detailed formulation of their samples in deference to their intellectual property rights. Additionally, it was agreed that the identification of the material suppliers would not be revealed.

Seven suppliers responded with samples. One sample from each supplier was selected, plus one CaF_2 sample for reference, and the test was started. The samples were arranged in two rows of four. Thus, the two front samples received the greatest fluence, and the following samples received a fluence level decreased by the reflections and absorption of the preceding samples. The actual fluence incident on the samples varies over a range of 0.063 to 0.095 mj/cm^2.

3 EXPERIMENTAL MARATHON RESULTS

3.1 Wavefront Distortion

At 10B pulses, a phenomenon coined “rarefaction” was noticed. It is similar to densification, but of opposite sign. In densification, the density of the fused silica is increased, which shortens the physical path through the material, but the index of refraction is increased to a greater extent, so that the net change is an increase in the optical path. In the effect seen at 10B pulses, the optical path was decreased in the irradiated area. This was noticed in sample H at 10B pulses and in samples C and F at a 12B pulse count.

In a test to verify the sign of the phase-measuring-interferometer data and confirm the rarefaction, two samples, C and H, were irradiated with approximately 100M pulses at a fluence of 3 mj/cm^2 in a separate area of the sample. This was expected to induce normal densification, and, in fact, it did result in densification in both samples. Each of the two samples then had two regions of irradiation: a low fluence region that produced rarefaction and a high fluence region that produced densification. A typical interferometer plot of sample H plot at 12B pulses is shown in Figure 1. For that sample, the optical path length is increased by 30 nm (3.8 nm/cm) for the high fluence exposure area and decreased by 12 nm (1.5 nm/cm) for the low fluence area.

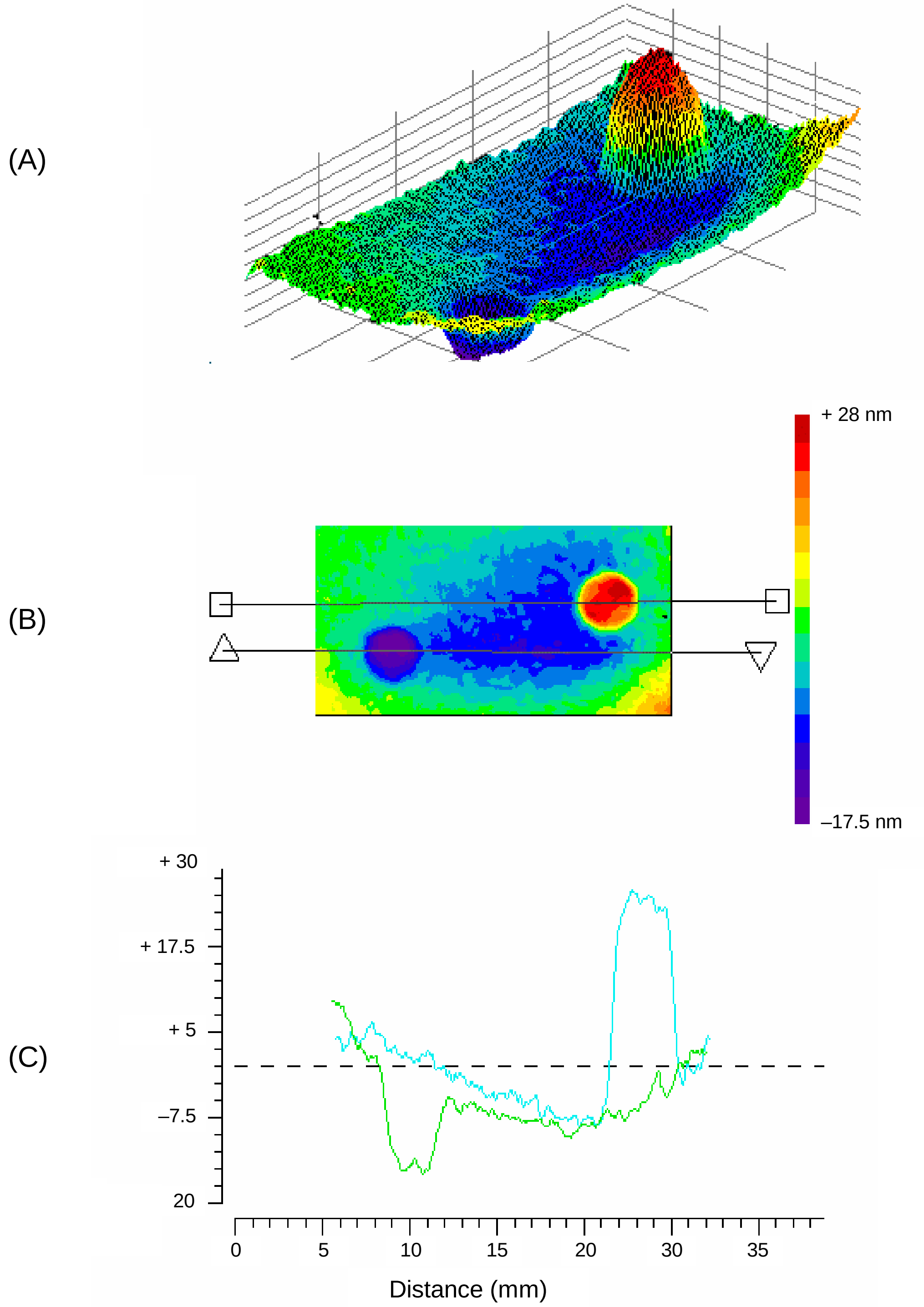


Figure 1 Wavefront Distortion Sample H

As the test continued, more samples showed the rarefaction, which increased with increasing pulse count. At 40B pulses, five of the samples showed rarefaction ranging from 22 to 45 nm (2.8 to 5.6 nm/cm). Two of the seven samples showed no wavefront distortion, either densification or rarefaction, within ability to measure, which is in the range of 3 to 5 nm. The distortion of the five samples is shown in Figure 2.

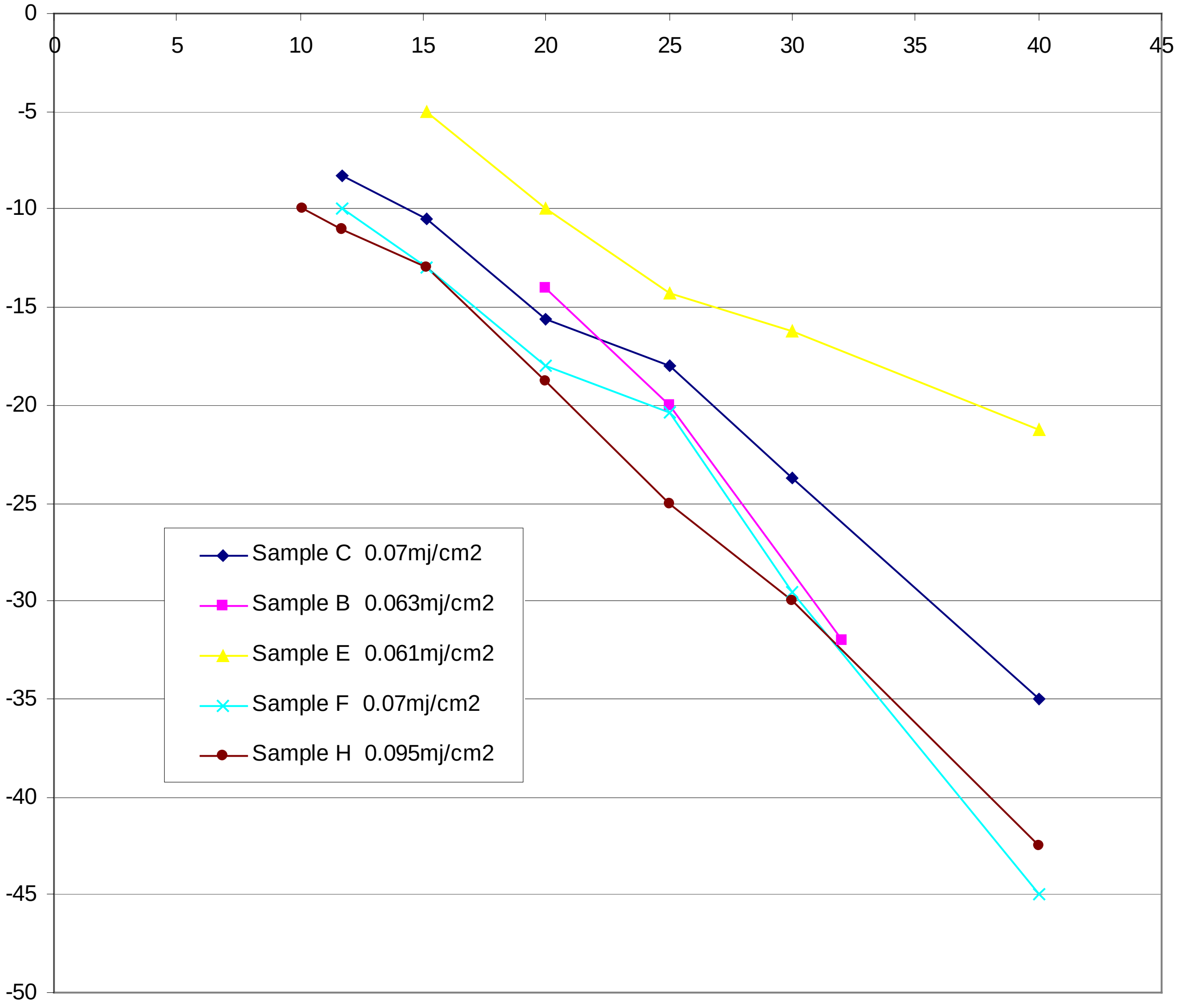


Figure 2 **Wavefront Distortion of Five Grades of Fused Silica Under Low-Fluence Irradiation**

The wavefront distortion data was presented to lens designers and tool manufacturers to ascertain the effect on lens aberrations. The level of concern was mixed among manufacturers, but they unanimously agreed that they needed scaling data to accurately predict lens aberrations. They needed to know how the densification/rarefaction scaled with fluence.

At that point, the marathon test was halted and the test chamber was reconfigured to conduct a scaling test.

4 SCALING LAW TEST

4.1 Test Configuration

The scaling law test is configured so that each sample is irradiated by four beams of varying fluence. The test configuration is shown in Figure 3.

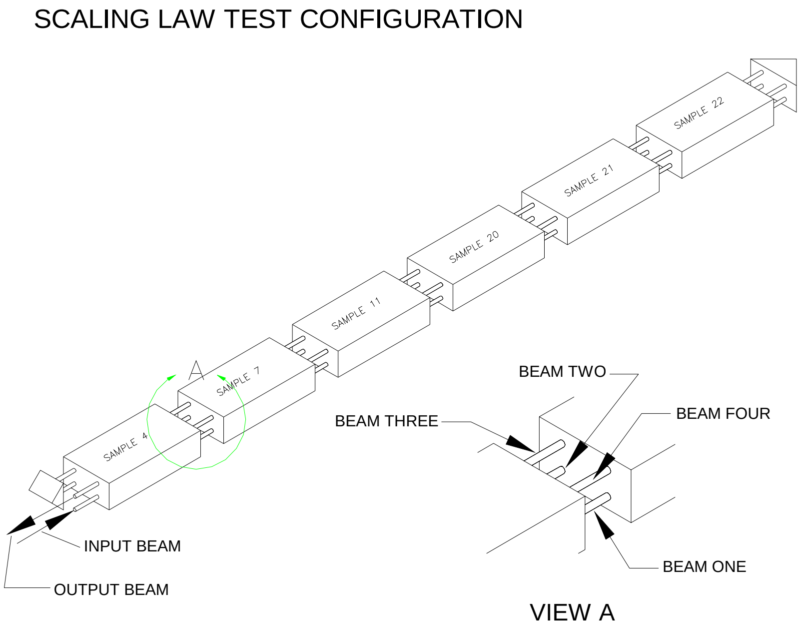


Figure 3 Scaling Law Test Configuration

The input beam (beam 1) irradiates all six samples in series and then is directed by the righthand prism back through the same samples as beam 2, displaced horizontally by about 2 cm. Beam 2 irradiates all six samples and then is directed back by the left prism as beam 3, displaced vertically by about 1 cm. Beam 3 traverses the samples and is then displaced by 2 cm and directed back through the samples as beam 4. In that manner, four beams are generated.

The fluence level of each pass through the samples is reduced by the absorption and surface losses of the samples, plus the losses in the turning prisms. The beam is attenuated by a factor of about 2.85 for each pass through six samples and the turning prism. The fluence level for each pass of each sample is shown in Table 1.

Table 1 Fluence Levels (mj/cm^2) for Scaling Law Test

Pass	Sample 4	Sample 7	Sample 11	Sample 20	Sample 21	Sample 22
1	0.2000	0.1714	0.1470	0.1260	0.1080	0.0926
2	0.0325	0.0379	0.0442	0.0516	0.0601	0.0702
3	0.0246	0.0211	0.0181	0.0155	0.0133	0.0114
4	0.0040	0.0047	0.0054	0.0063	0.0074	0.0086

4.2 Measurements

All samples are removed from the test chamber for measuring wavefront distortion and birefringence at intervals of two billion pulses.

Wavefront distortion, indicative of densification or rarefaction, is measured using a Zygo phase measuring interferometer (PMI). The Zygo is capable of measuring wavefront distortion to a level of 3 to 5 nm.

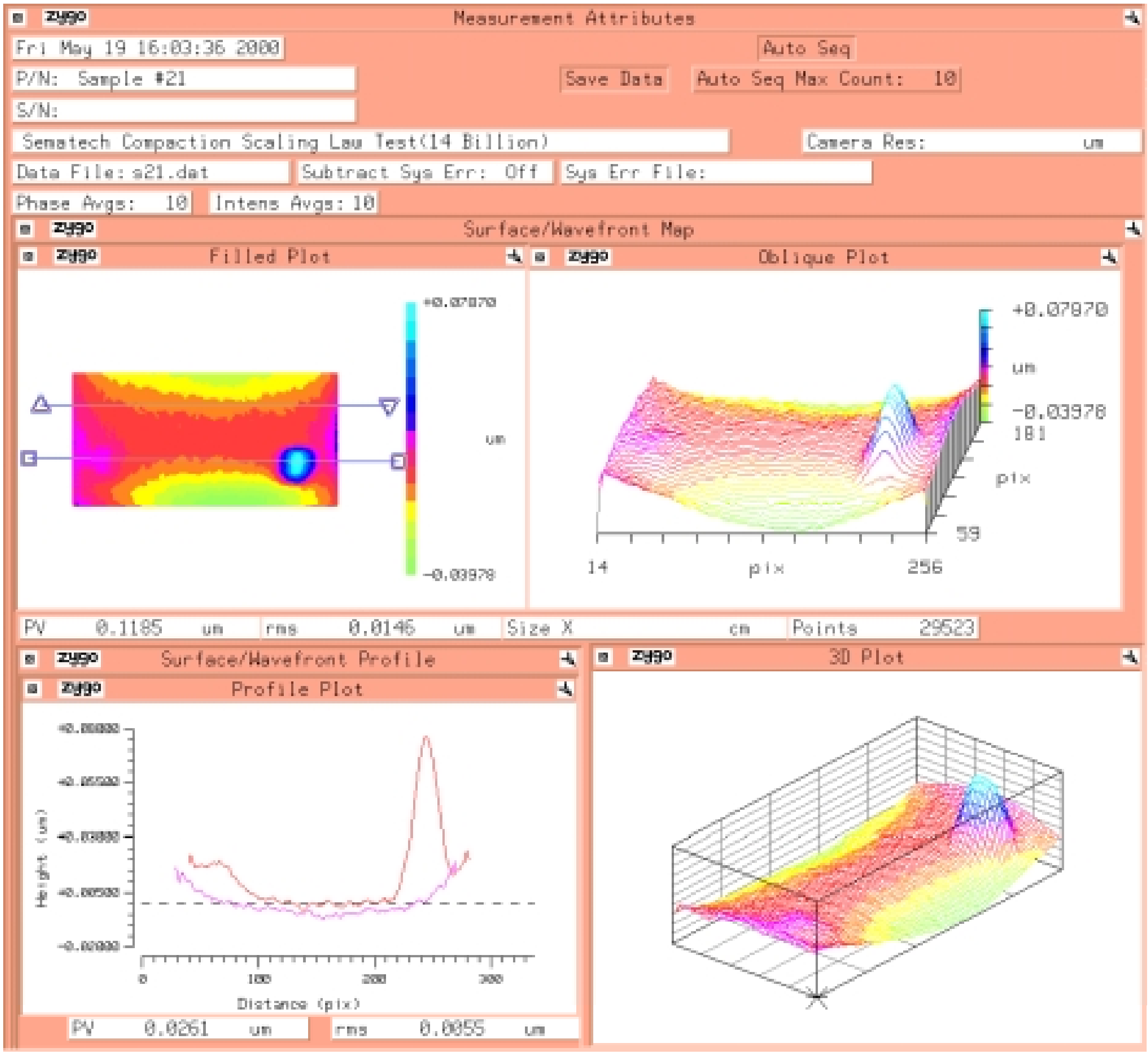
Birefringence is measured using an Exicor 120 manufactured by Hinds Instruments. This instrument is capable of scanning a selected area of the sample and measuring both phase and magnitude of the birefringence over that area. Birefringence is the condition whereby the index-of-refraction is a function of the polarization angle of the light source. Some crystals are naturally birefringent. In non-crystalline materials, birefringence is commonly caused by internal stress in the material.

5 MEASURMENT DATA

5.1 Wavefront Distortion

5.1.1 Sample 21

At 14 billion pulses, the samples show varying degrees of densification/rarefaction. Figure 4 is the Zygo printout for sample 21. The two figures on the right are 3D representations of the wavefront. The positive or upward distortion is indicative of densification. The filled plot in the upper left is a chromatic representation, and the graph in the lower left is a cross section taken at the two marker lines in the filled plot. Exposure beam 1 (lower left of the filled plot) clearly causes densification of about 70 nm, and beam 2 (lower right) results in about 12 nm densification.



Fri May 19 16:03:36 2000
P/N: Sample #21
S/N:
Auto Seq Max Count: 10
Sematech Compaction Scaling Law Test(14 Billion)
Camera Res: um
Data File: s21.dat
Subtract Sys Err: Off
Sys Err File:
Phase Avgs: 10
Intens Avgs: 10

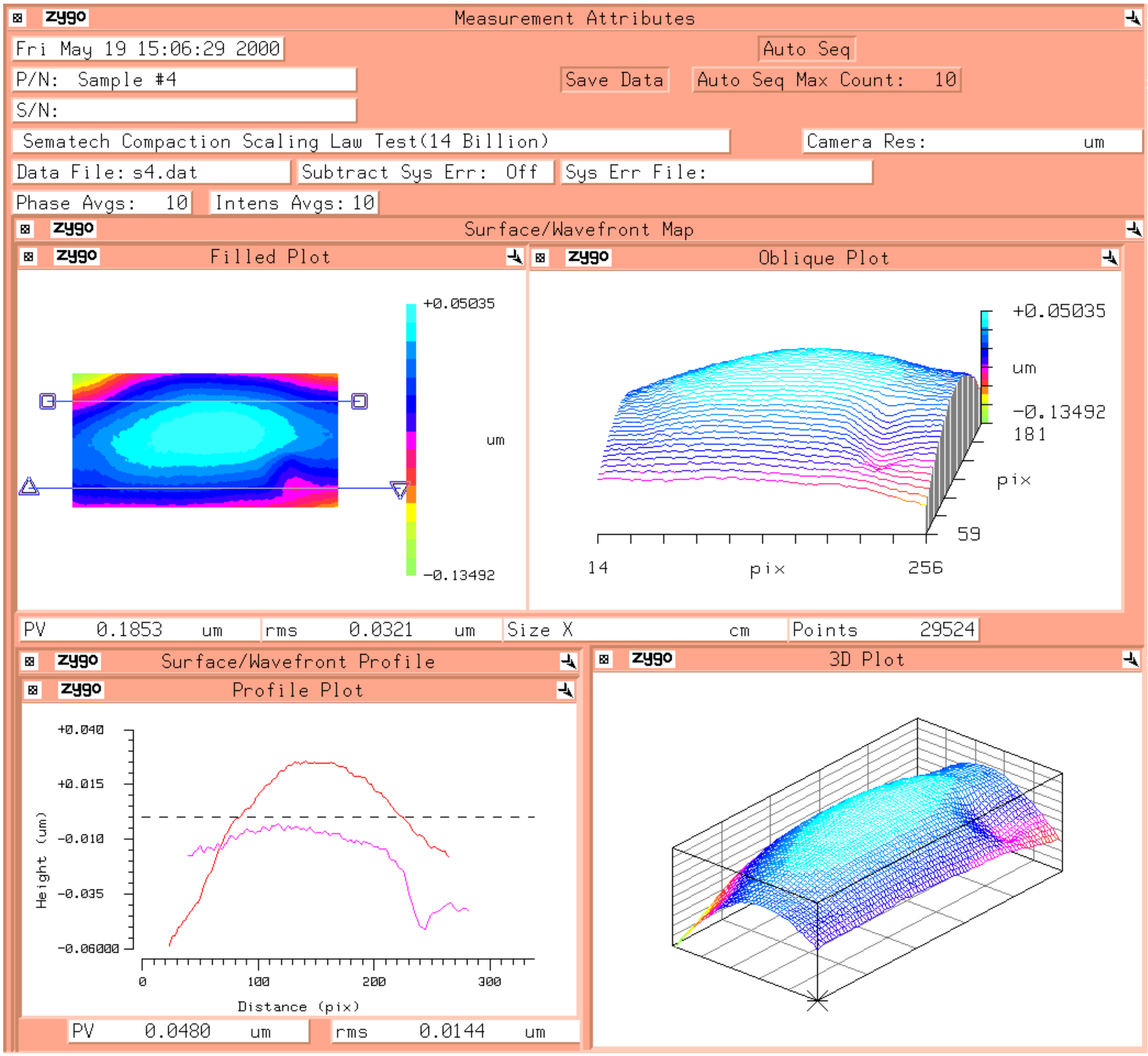
PV 0.1185 um
rms 0.0146 um
Size X cm
Points 29523

PV 0.0261 um
rms 0.0055 um

Figure 4 Wavefront Distortion Sample 21

5.1.2 Sample 4

Sample 4 shows rarefaction as can be seen in Figure 5. The two 3D plots on the right show an indent, which is indicative of rarefaction. Beam 1 shows a rarefaction of about 25 nm. Beams 2 through 4 show little or no effect at 14 billion pulses. Beam 2 has approximately one-sixth the fluence level of beam 1.



Fri May 19 15:06:29 2000

P/N: Sample #4

Auto Seq Max Count: 10

S/N:

Sematech Compaction Scaling Law Test(14 Billion)

Camera Res: um

Data File: s4.dat

Subtract Sys Err: Off

Sys Err File:

Phase Avgs: 10

Intens Avgs: 10

PV 0.1853 um

rms 0.0321 um

Size X cm

Points 29524

PV 0.0480 um

rms 0.0144 um

Figure 5 Zygo Print of Wavefront Distortion—Sample 4

5.1.3 Wavefront Distortion—First Beam—All Samples

The wavefront distortion of all samples can be seen in Figure 6. Samples 21 and 22 show densification, increasing with pulse count, possibly linearly. Samples 4 and 11 show rarefaction, also increasing with pulse count. Sample 7 seems to show initial densification, changing to rarefaction at about 4 billion pulses. This could be caused by a subtle change in fluence at that sample, or it could be some other effect that is not understood at this time. The magnitude is small; 12 nm rarefaction corresponds to 1.5 nm/cm for the 8 cm samples. Sample 20 also shows no clear trend out to 14 billion pulses.

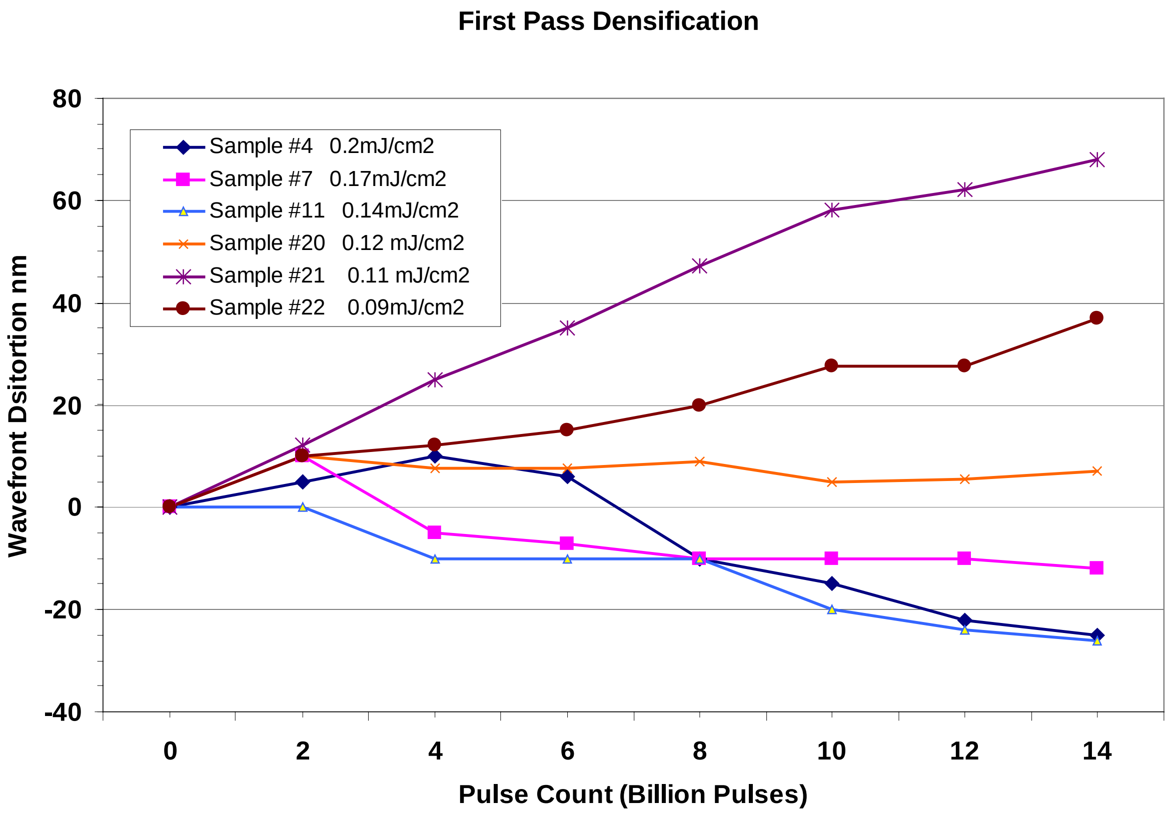


Figure 6 Beam 1—Wavefront Distortion Through 14 Billion Pulses—All Samples

5.1.4 Wavefront Distortion—Second Beam—All Samples

Figure 7 shows the effect of beam 2. Note the scale change with respect to Figure 6. The general trends are same. Samples 21 and 22 show clear densification, whereas the rest show rarefaction. Note that the magnitudes are smaller and are approaching the limits of the Zygo measurement instrument, which is on the order of 3 to 5 nm.

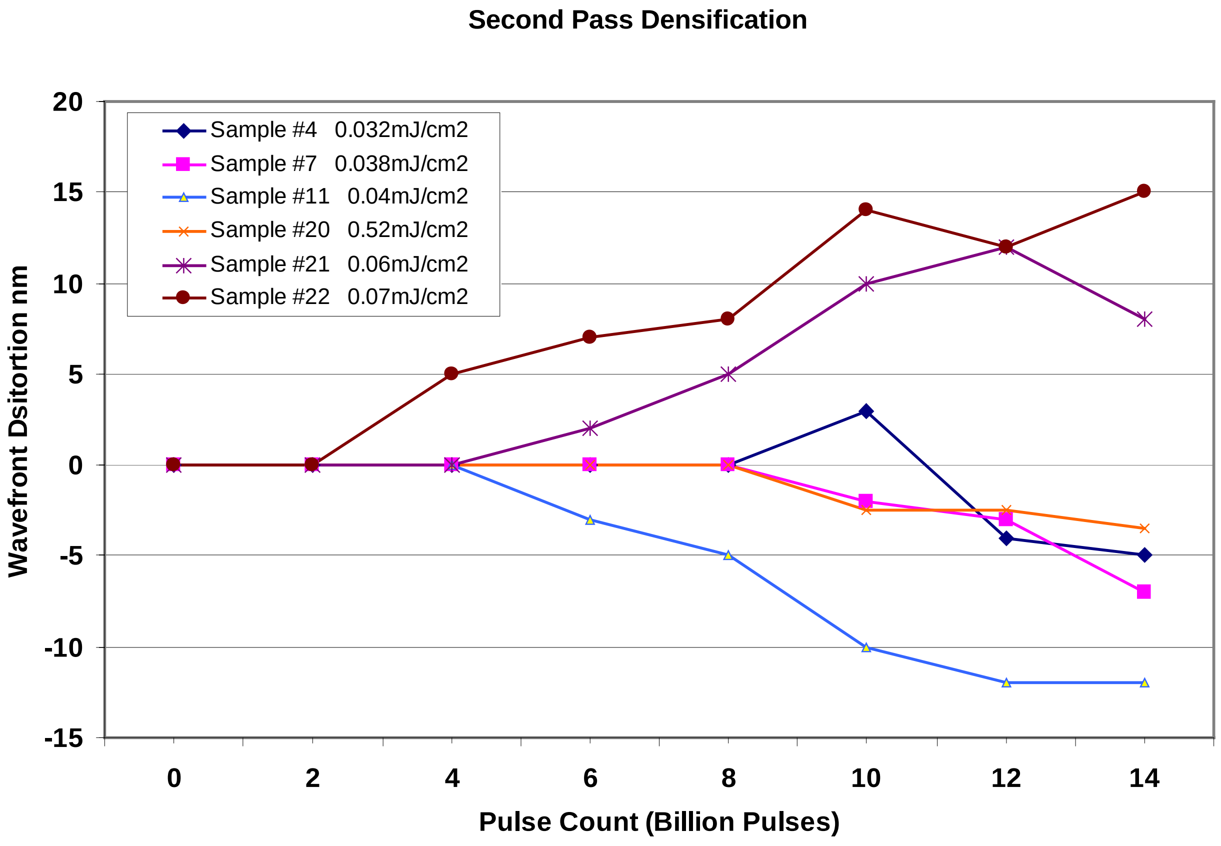


Figure 7 Beam 2—Wavefront Distortion Through 14 Billion Pulses—All Samples

5.2 Birefringence

Birefringence is a condition whereby the index of refraction is a function of the angle of polarization. The magnitude is expressed as the normalized difference in the optical path lengths of the two polarizations. Some crystals, such as lithium fluoride, are naturally birefringent. Birefringence in fused silica generally is caused by an internal strain in the material, which can result from the annealing process used in manufacturing the fused silica. Strain is always generated by any densification that results from ultraviolet (UV) irradiation.

Birefringence of sample #11 is shown in Figure 8, which is a 3D representation of the magnitude of the birefringence. The X and Y axes represent position in mm, and the Z axis is the magnitude of the birefringence. The effect of beam 1 can be seen in the upper left as a spike of approximately 20 nm. Beam 2 shows up in the upper right with a magnitude of approximately 2 to 3 nm. Note that the birefringence from beam 2 peaks in an annulus around the periphery of the exposed area, whereas birefringence caused by beam 1 has a sharp peak in the center. The reason for this difference is not clear, but has been observed in other tests.

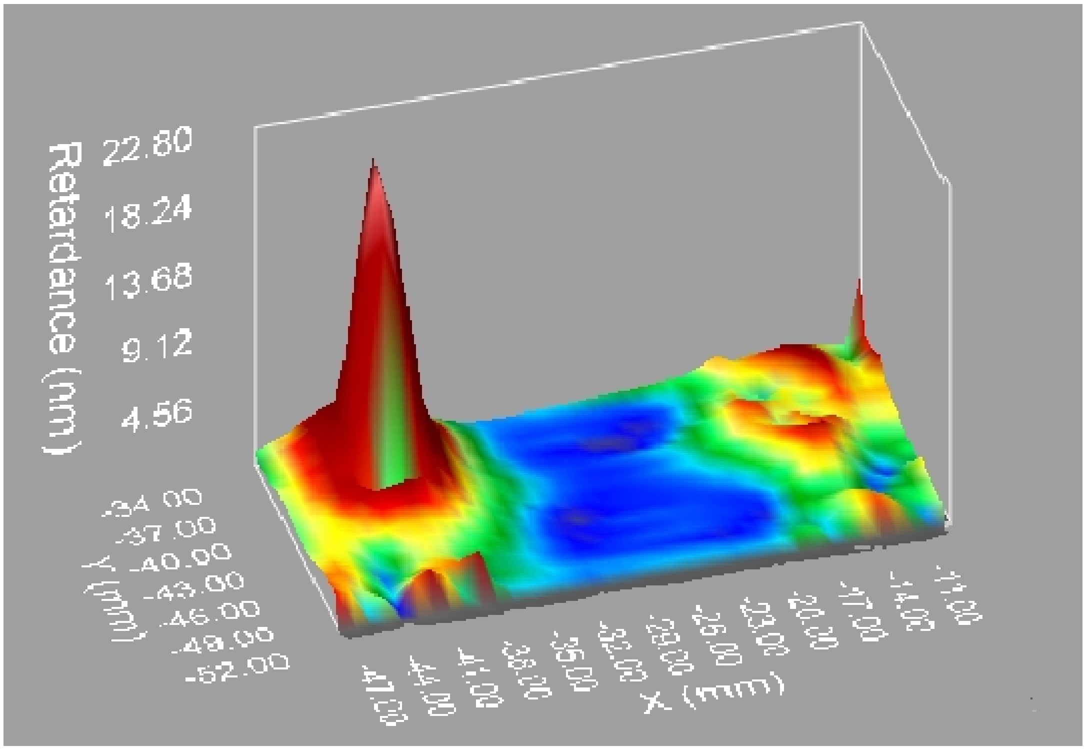


Figure 8 Birefringence Magnitude of Sample #11

Birefringence for all samples is shown in Figure 9 and Figure 10.

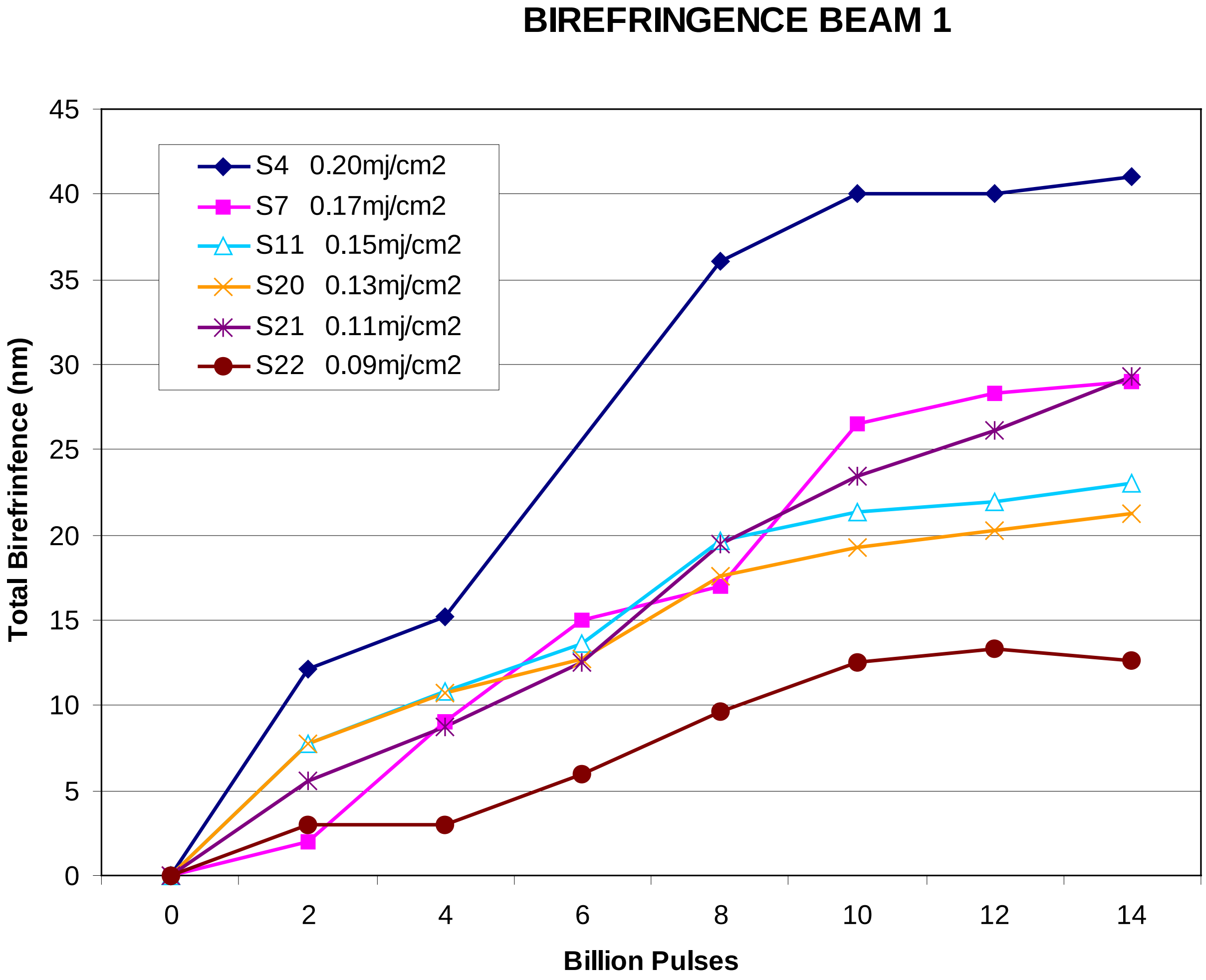


Figure 9 Beam 1—Birefringence Through 14 Billion Pulses—All Samples

Figure 9 shows birefringence resulting from beam 1 for all samples. The magnitude ranges from 15 to 40 nm. Since the samples are 8 cm long, this corresponds to a range of 2 to 5 nm/cm. The birefringence generally increases with pulse count, but there is variation among grades.

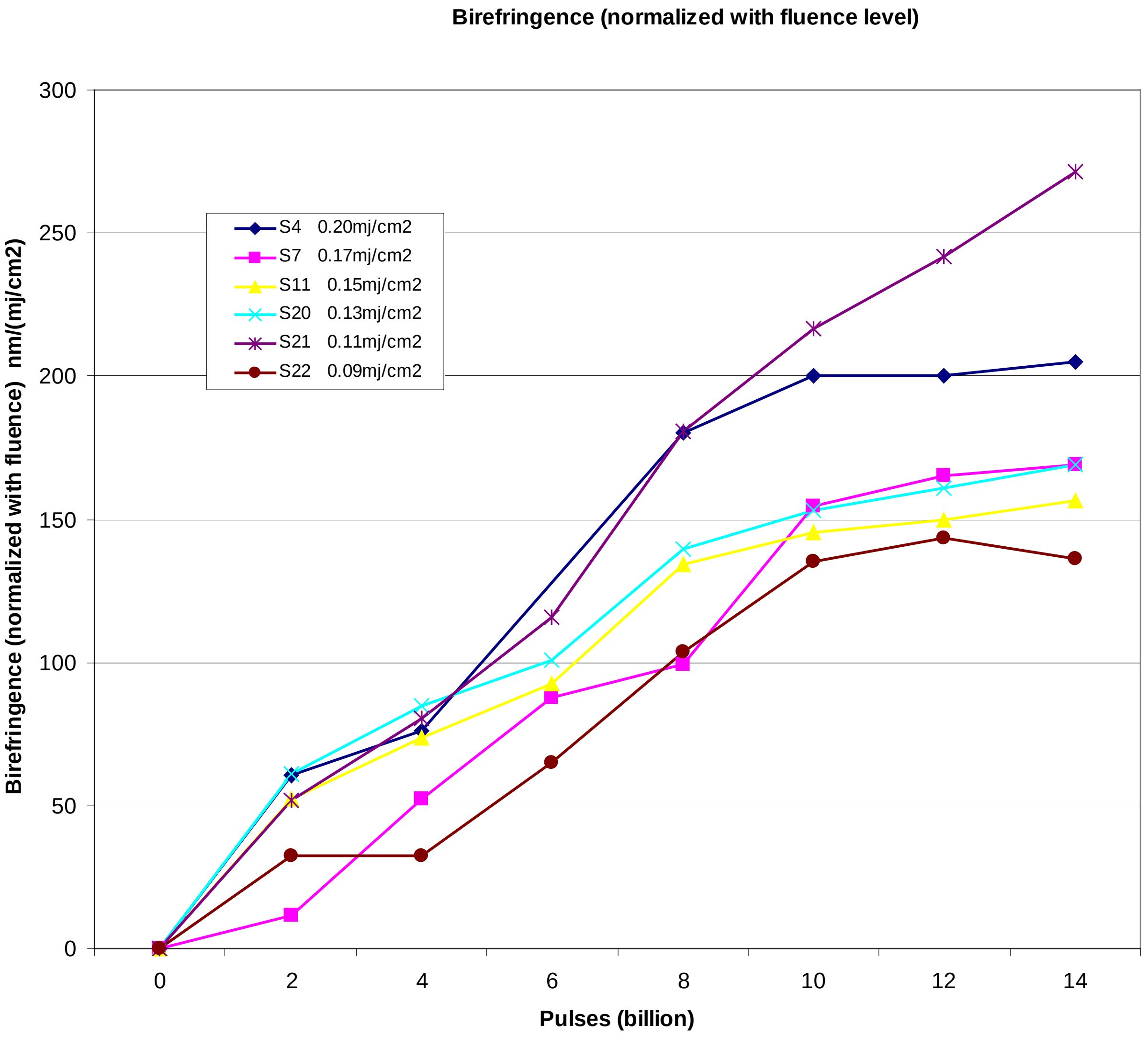


Figure 10 **Beam 1—Birefringence Normalized for Fluence Through 14 Billion Pulses—All Samples**

Figure 10 shows birefringence normalized for fluence. As can be seen, there is a significant fluence dependence, as there is a tighter grouping of data for the normalized data.

It is interesting to note that there seems to be a saturation at approximately 10 billion pulses for all of the samples except sample #21. The mechanism for saturation is not yet understood.

6 CONCLUSIONS—EFFECT ON IMAGE QUALITY

6.1 Wavefront Distortion—Effect on Imaging

Wavefront distortion as evidenced by the Zygo data will affect image quality in that the imaging wavefront will be distorted. The allowable wavefront distortion is a function of the optical design, but is generally a fraction of a wavelength (at the exposure wavelength).

The wavefront distortions of up to 60 nm (7.5 nm/cm) represent a distortion of 0.3 λ (0.04 λ/cm). The impact on the image quality will be a function of the lens design and the path length through the fused silica.

6.2 Birefringence—Effect on Imaging

The effect of birefringence is similar to wavefront distortion, except that it depends on the polarization of the source. For a non-polarized source, birefringence is simply another distortion term in the imaging wavefront. Some exposure systems, particularly catadioptric types, use polarization as an important parameter of the system. In these cases, birefringence can alter the polarization and can introduce additional error terms. The magnitude of those error terms is a function of the lens design and the optical path length through the material.

6.3 Total Effect on Imaging Quality

The lens designers and exposure tool manufacturers need to understand the scaling laws of these distortions to accurately determine the effect on image quality. At the conclusion of these tests, the data will be made available, so that an accurate assessment can be made.

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