# Production-Ready 2kHz KrF Excimer Laser for DUV Lithography

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## ABSTRACT

Now that 1000 Hz KrF excimer laser based DUV lithography tools are firmly established in production, emphasis is shifting from development towards improving the productivity and profitability of the manufacturing process, thereby reducing the cost per wafer. In this arena, laser manufacturers are competing now not only on performance but also on cost and productivity enhancements that the laser can offer to the lithography process.

While the conventional wisdom towards reducing the laser's contribution to the cost of the lithographic process has been and will continue to be reducing the laser cost of operation, laser-based enhancements in system throughput offer another powerful advantage to semiconductor manufacturers. One obvious way to achieve this it to increase the repetition rate, and therefore output power, of the laser.

Current production excimer lasers operate at 1000 Hz, so an increase to 2000 Hz cuts the exposure time in half. When exposure time is limiting the productivity of the microlithography step, a higher repetition rate will offer a direct throughput increase. Computer modeling of a 300 mm scanner with a 250 mm/second stage using a 30 mJ/cm$^2$ resist indicates that throughput enhancements greater than 30% are possible over the same scanner using a 1000 Hz laser.

Alternatively, a 2000 Hz laser allows twice the number of pulses to be delivered in the same time. Therefore, a 60 mJ/cm$^2$ resist can be exposed by a 2000 Hz laser in the same time it would take to expose 30 mJ/cm$^2$ resist with a 1000 Hz laser. The higher pulse count also improves the energy dose stability and therefore CD control.

In this paper, Cymer reports on the industry's first production-ready 2000 Hz excimer laser system. This will start with development of the core technologies that allowed for doubling of the laser output power compared to the predecessor 1000 Hz systems. Data demonstrating the system's optical characteristics will be presented, particularly the superior energy dose stability characteristics which will allow lithographers to make full use of the 2000 Hz operating frequency without compromising CD control.

We will also discuss additional productivity enhancements, such as modular construction, improved diagnostic monitoring, and on-line documentation.

Finally, the results of preliminary lifetime and reliability tests will be reported.

**Keywords:** Deep-Ultra-Violet, Lithography, KrF, Excimer, Reliability, Compliance, Lifetest

## 1. OVERVIEW

The ELS-6000 takes Cymer's proven KrF 248nm technology a major step forward: enabling new generation of lithography and significant gains in productivity. With its 0.6pm FWHM bandwidth, 2.0pm spectral bandwidth at 95% integrated energy and 0.5% energy dose stability at a 2000 Hz repetition rate, Cymer's end-users have the ability to increase their production throughput by 13 percent to over 30 percent – or maintain current throughput using fewer lithography tools. Key laser performance specifications are shown in Table 1.


Optical Microlithography XII, Luc Van den Hove, Editors,
Proceedings of SPIE Vol. 3679 (1999) · 0277-786X/01/$15.00

| Parameter | ELS-5000 | ELS-5010 | ELS-6000 |
|---|---|---|---|
| Wavelength | 248 nm | 248 nm | **248 nm** |
| Pulse Energy | 10 mJ | 10 mJ | **10 mJ** |
| Repetition Rate | 1000 Hz | 1000 Hz | **2000 Hz** |
| Bandwidth | ≤ 0.8 pm | ≤ 0.6 pm | **≤ 0.6 pm** |
| Energy Dose Stability | ≤ ± 0.8%<br>50 Pulse Window | ≤ ± 0.6%<br>40 Pulse Window | **≤ ± 0.5%<br>32 Pulse Window** |
| Introduced | 2Q '96 | 1Q '98 | **4Q '98** |

**Table 1 Key ELS-6000 Performance Specifications (Fully Lined Narrowed)**

Laser performance can have a significant impact on the overall performance of the lithography tool. Table 2 shows the correlation between key laser parameters and integrated system performance.

| Laser Parameters | | Refractive System | Catadioptric System |
|---|---|---|---|
| Spectral Bandwidth | ⇨ | Resolution, Depth of Focus | 10-50X less sensitive |
| Wavelength Stability | ⇨ | Focus | 10-50X less sensitive |
| Output Power | ⇨ | Throughput | Same as refractive |
| Repetition Rate | ⇨ | Energy Dose Accuracy, Speckle Reduction, Throughput | Same as refractive |
| Pulse-to-Pulse Energy Stability | ⇨ | Exposure Accuracy, | Same as refractive |
| Beam Profile, Pointing Stability | ⇨ | Exposure Uniformity, Illuminator Efficiency | Same as refractive |
| Polarization Stability | ⇨ | Illuminator Efficiency | Same as refractive |
| Spatial Coherence | ⇨ | Speckle, Exposure Uniformity | Same as refractive |

**Table 2 Laser performance parameter and their impact on stepper/scanner performance**

The laser's new modular platform, shown in Figure 1, provides Cymer's customers with two key benefits: shorter service and maintenance times since all modules can be serviced from the front of the system and an ability to upgrade their ELS-6000 platform in the future with the latest Cymer developments to maintain their competitive edge.

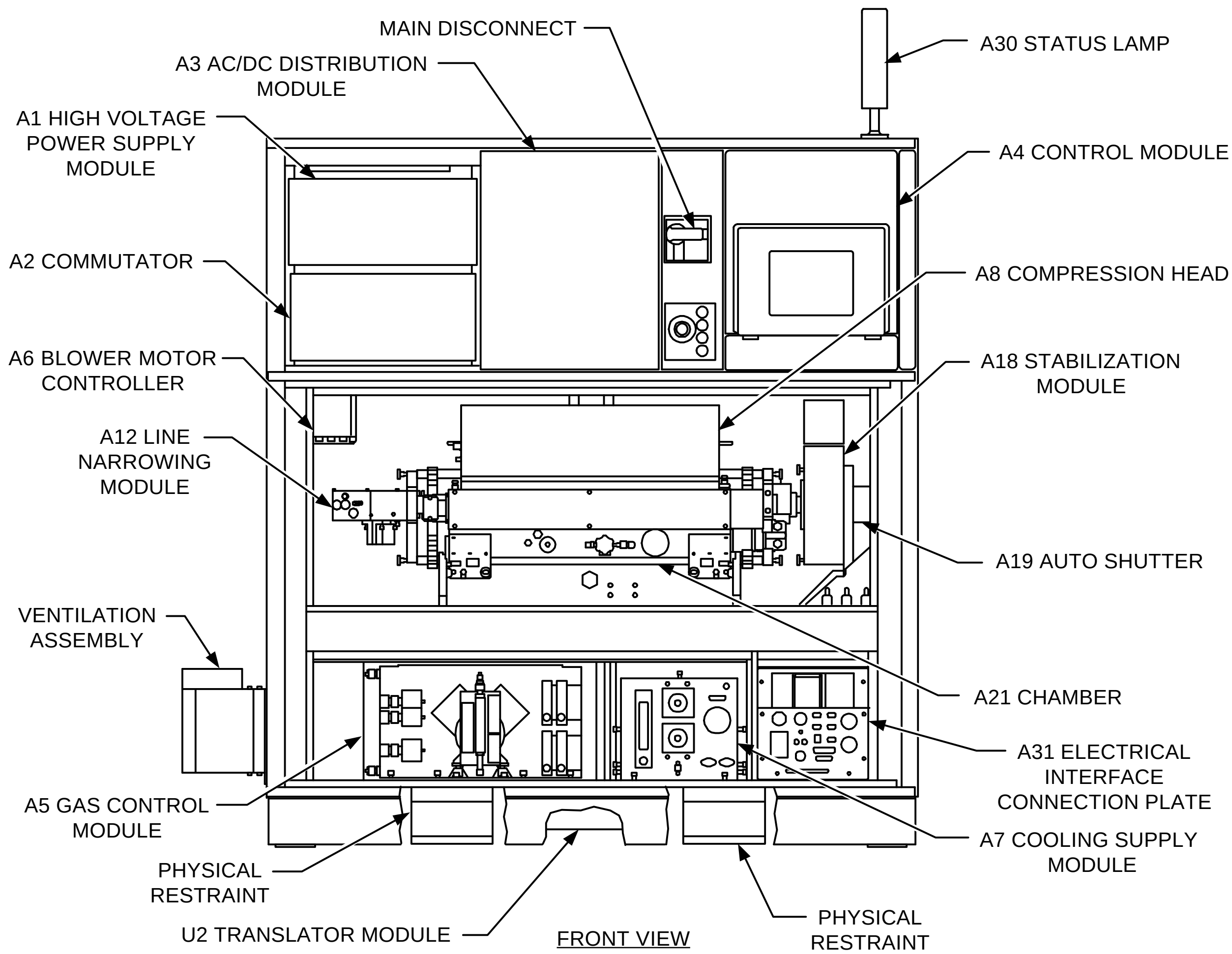


**Figure 1 ELS-6000 Modular construction**

**Key module improvements over previous lasers:**

- Line-Narrowing Module (LNM) uses higher stability optical components to control the laser's spectral bandwidth to ≤0.6 FWHM, ≤2.0pm, 95% energy integral
- Solid State Pulsed Power Module (SSPPM) features tighter voltage regulation to provide better pulse to pulse energy control, enabling a more stable and uniform dose energy output during exposure
- High Efficiency Chamber's (HE Chamber™) uses an enhanced pre-ionization scheme to extend chamber performance
- Stabilization module features an increased bandwidth measurement resolution
- Optional Pentium™ powered service touch-screen provides instant access to maintenance and service data
- Modular AC/DC Distribution Module uses modular, rail-mounted components to significantly reduce service time

## 2. OPTICAL PERFORMANCE

One of Cymer's primary goals in development of the ELS-6000 was to achieve reliable 2 kHz operation with little or no increase in required blower speed and power. This has been achieved by improvements in discharge gas flow geometry (shown in Figure 2), which have reduced the required clearing ratio by a factor of 2. Therefore, the ELS-6000 operates at almost the same blower speed as ELS-5000. This allows us to employ the same high reliability technology for blower, bearing and fan motor components. As an example, the estimated MTBF on the chamber bearings is 3400 hours, based upon a combination of life testing under operating conditions, accelerated life testing, and model predictions.

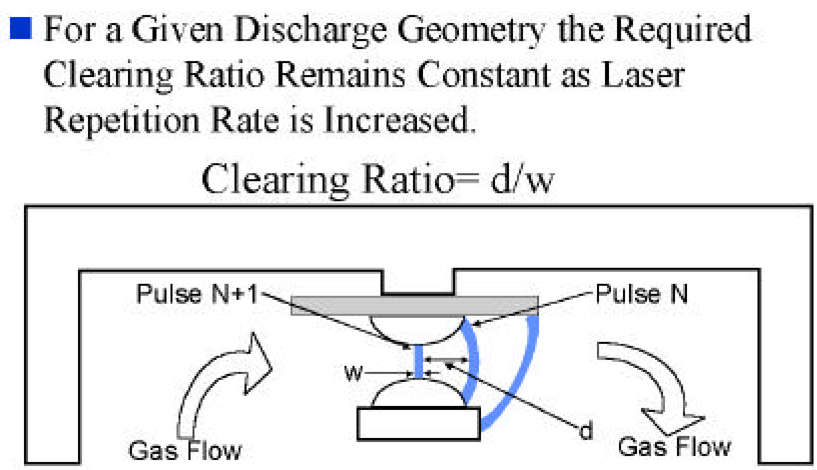


**Figure 2 Improved gas flow minimizes the required blower speed**

Beyond simple improvements in gas flow geometry, ELS-6000 also incorporates an improved discharge chamber configuration and construction material. This improvement manifests itself primarily in reduced spatial jitter and improved efficiency. Spatial jitter is important, because it is a direct contributor to both pulse to pulse energy instability and pulse to pulse wavelength instability, each of which has an impact on lithographic performance.

Benefits of efficiency improvements are increased reliability and lifetime of the discharge chamber, which is the largest single contributor to the laser's cost of operation. As shown in Figure 3, the laser is capable of outputting much greater than the rated 10 mJ at all repetition rates up to and beyond 2000 Hz. This performance overhead projects to reliable, long-life operation of the discharge chamber, even as the chamber itself and resonator optics degrade in performance over their specified lifetimes.

The use of improved materials in the discharge chamber results in a reduction in the buildup of gas phase contaminants during laser operation. This translates directly into extended gas maintenance intervals for the end user. Contaminant reduction also contributes to the extension of discharge chamber lifetime.

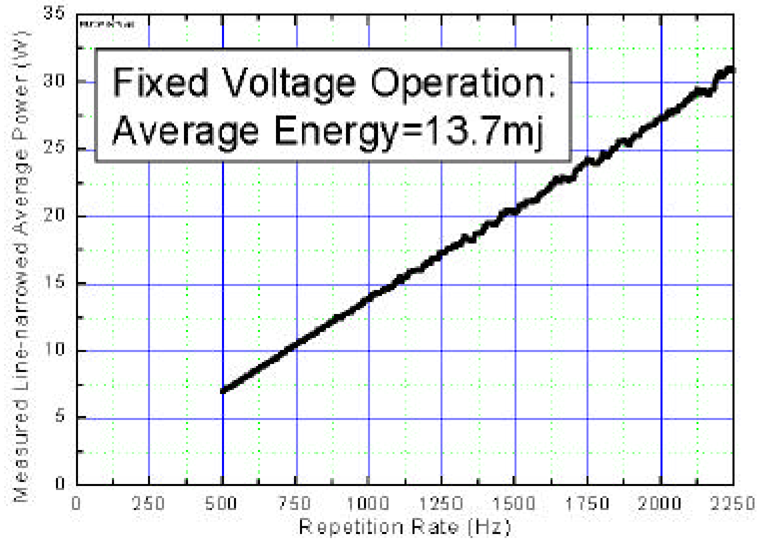


**Figure 3 Increased operating range**

Another improvement incorporated in the ELS-6000 is the electrical drive circuit. The design is based upon our field-proven ELS-5000 Solid Stated Pulsed Power Module.

Some of the specific improvements are:

a) Thermal management to support reliable 2000 Hz operation
b) Serviceability to improve MTTR
c) Circuit optimization for improved discharge chamber performance and lifetime.
d) Voltage regulation resulting in improved pulse energy stability

As with the laser efficiency, the pulse energy stability is not only improved but maintained to repetition rates in excess of 2000 Hz. This design change results in improved discharge chamber lifetime as well as the improved pulse energy stability shown in Figure 4.

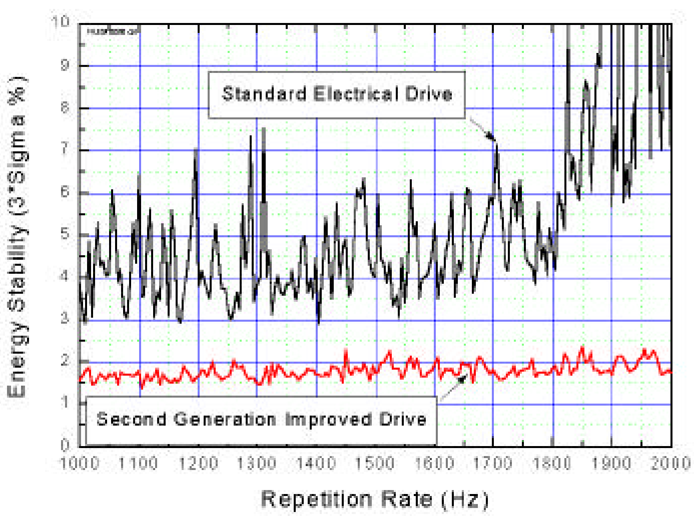


**Figure 4 Drive circuit changes result in improved dose energy stability**

This improvement in fundamental pulse energy stability translates directly into improved energy dosage stability, which is critical for high performance scanner operations. An example of the typical performance in an operating mode characteristic of actual field use is shown in Figure 5. This graph represents the worst case (most positive and most negative) measured dose errors, using a 32 pulse sliding window, for each burst in a typical 1000 burst sequence.

The data shown in these figures is analyzed using a 32 pulse sliding window, which is well matched to scanner stage speeds in the range of 250-500 mm/second. The upper graph in this figure shows the measured worst case positive and negative percentage dose errors in each burst, for a train of 1000 consecutive bursts. The lower graph shows the same data plotted in histogram format on a semi-log scale.

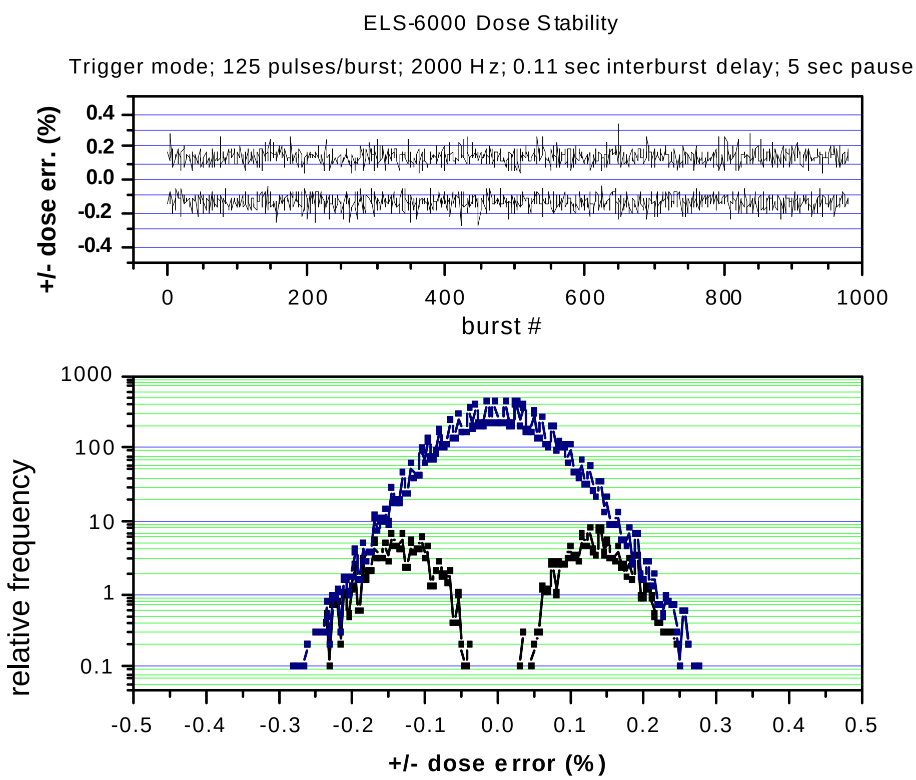


**Figure 5 Energy Dose stability in a user environment**

To mitigate the possible effects of thermally-induced optical distortion on laser beam spatial properties, ELS-6000 incorporates excimer grade $CaF_2$ for use in all transmissive resonator optical elements.  This has resulted in great improvements not only in initial performance (Figure 6) but also lifetime of the optics.

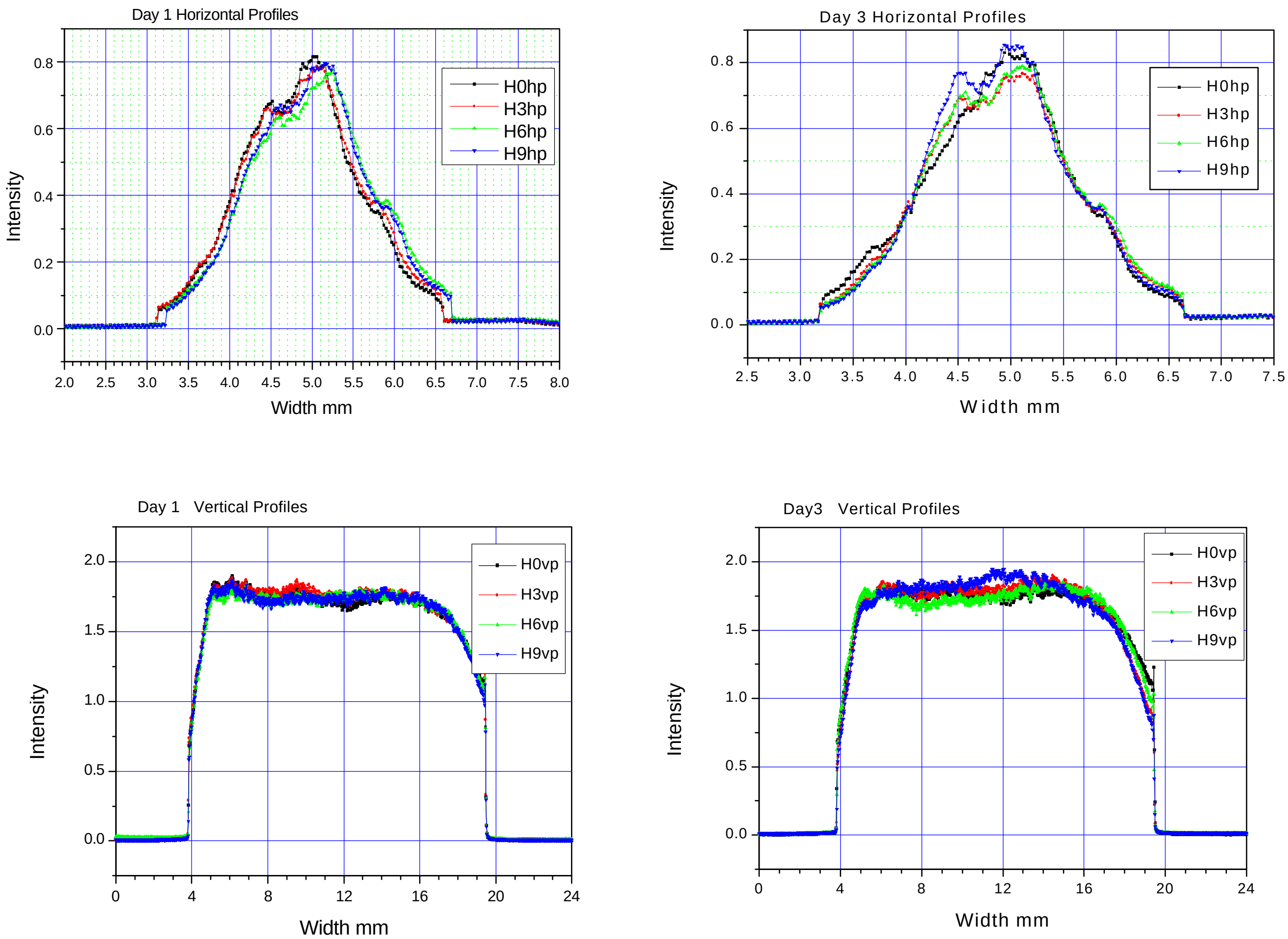


**Figure 6 Beam profile stability over a 3-day period**

In summary, the optical performance of ELS-6000 is equal or superior to current generation 1-kHz excimer sources in all major performance categories even though the average optical power has been increased by a factor of two.  This statement is based not just on a single system, but from the measured performance data collected from a sampling of ELS-6000 lasers prior to shipment (Table 3).  These data demonstrate that the technology and manufacturing processes have reached the necessary level to be considered production ready.

| SELECTED PERFORMANCE DATA FROM SEVERAL ELS-6000 SYSTEMS | | | |
|---|---|---|---|
| **System #** | **Dose Stability, 32 Pulses (%)** | **95% Integral Spectrum (pm)** | **FWHM Spectrum (pm)** |
| 1 | +/- 0.30 | 1.48 | 0.43 |
| 2 | +/- 0.35 | 1.80 | 0.42 |
| 3 | +/- 0.34 | 1.58 | 0.42 |
| 4 | +/- 0.45 | 1.74 | 0.46 |
| 5 | +/- 0.24 | 1.90 | 0.48 |
| **Mean** | **+/- 0.34** | **1.70** | **0.44** |
| **σ** | **+/- 0.08** | **0.17** | **0.03** |

**Table 3 Measured Optical Performance of ELS-6000 Systems**

## 3. LIFETEST RESULTS

Cymer is currently conducting its first extended lifetest of the ELS-6000 core technology configuration. The laser has accumulated about 8 billion shots since the test started in the fall of 1999. Some of the core laser modules (Line Narrowing Package, High Voltage Power Supply and Solid State Pulse Power Module) had already accumulated 1.4 billion shots when the life test was started. The Wavelength Control Module was upgraded during the test to implement a design upgrade and it has now 3 billion shots. The chamber bearings have accumulated over 2550 hours during testing.

To date, no failures have occurred and only minimum maintenance service has been required, the first occurring after 4.5 billion shots (optical alignment, re-calibration). At the end of 1998 the laser was shut-down for a week due to facility maintenance, with no noticeable impact on the laser gas. Since that time the laser has been running continuously, simulating different expected end-user operating modes. This is done to ensure that parameters such as wafer exchange time, exposure length, and die transit time have minimal impact on laser performance.

An extensive set of diagnostics is used to monitor every aspect of the laser's specified performance. This is equivalent to the test suite used to verify Cymer products prior to shipment, but with data acquisition enhancements which facilitate real-time monitoring of several parameters which are typically measured only intermittently in the standard test suite.

The operating voltage throughout the test is shown in Figure 7. A simple extrapolation of the data results in a projected chamber lifetime of approximately 10B pulses. The higher variability at the beginning of test is due to the fact that more experimental activities were conducted in that time frame. Figure 8 expands the same voltage trend near the last 2 billion shots. Note that during this latest portion of the test, the voltage increase has been negligible. It is worthwhile noting that the laser has been running with the same gas fill for the last 2 billion shots.

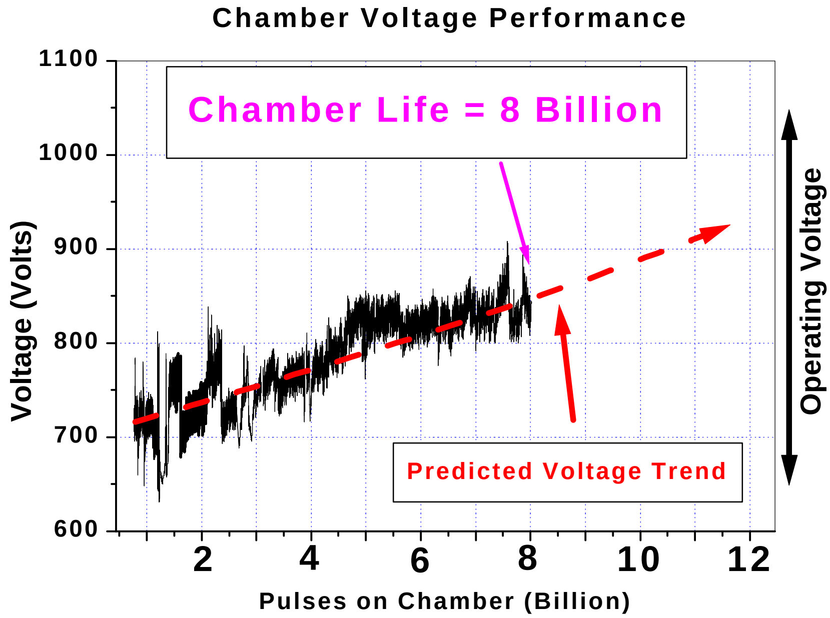


**Figure 7 System Lifetime Projection**

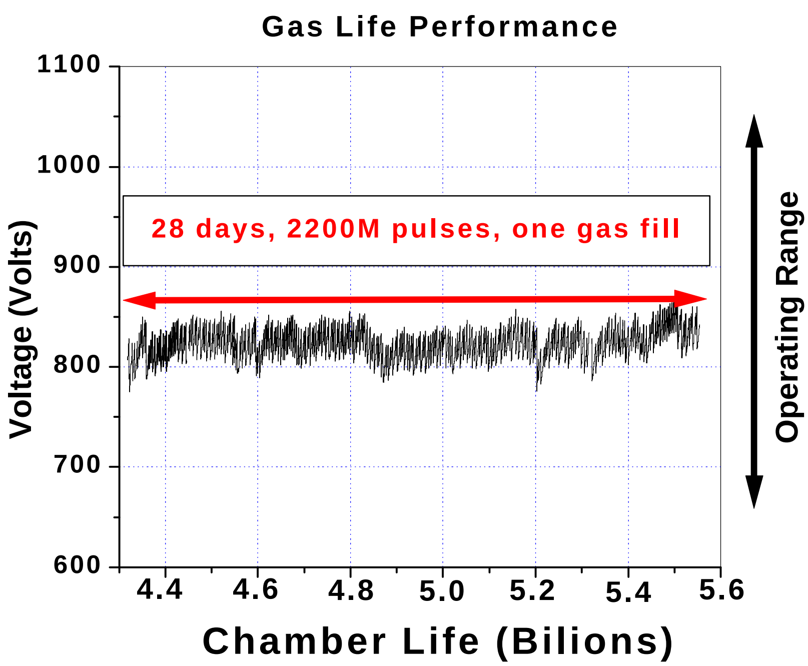


**Figure 8 Sample of chamber gas life**

Bandwidth (Figure 9) was measured by means of a double-pass grating spectrometer which has a resolution of approximately 0.12 pm. Measurements are typically taken in the morning after a night run, at a duty cycle of about 50%. This high duty cycle was chosen to ensure that thermal effects in the optics do not lead to degradation of the laser spectrum. The measurements are performed without any particular synchronization with gas injects. This explains the variability from day to day.

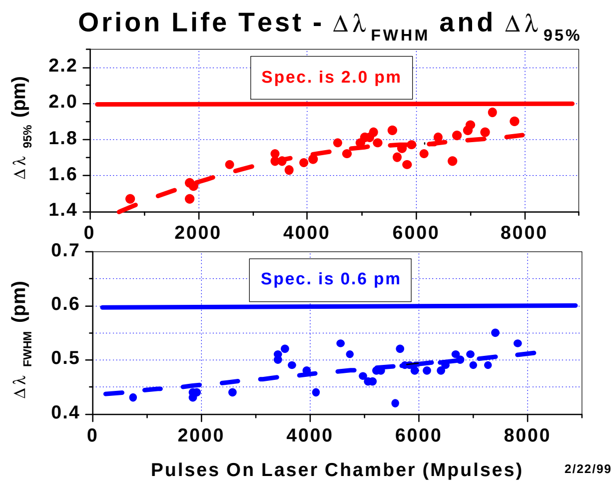


**Figure 9 Spectral performance over lifetime**

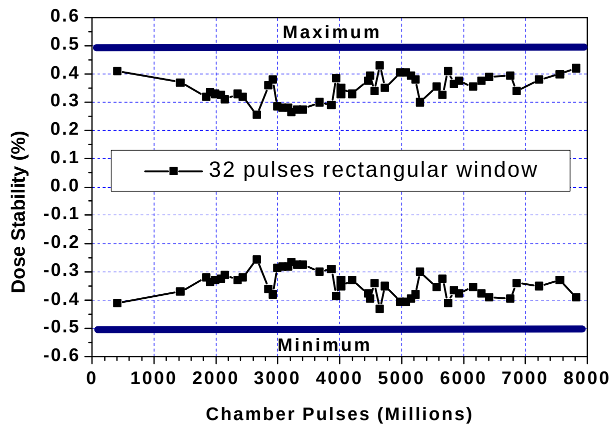


**Figure 10 Dose stability performance over lifetime**

The energy dose stability (Figure 10) was measured at a lower duty-cycle that better simulates a more typical end user operating condition. Note that the lower duty-cycle is more demanding for the dose stability performance of the laser.

In summary, the core technology modules of an ELS6000 system are currently being life tested. No failures due to performance or reliability have been observed. The projected module lifetimes are conservatively consistent with the product Cost of Operation targets.

## 4. LASER RELIABILITY

Early detection and elimination of failure modes and life limiting characteristics is central to Cymer's design for reliability methodology. In order to provide robust and mature designs at product introduction, Cymer has developed Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) Models of its laser systems for modeling and evaluation. These models are used to develop Critical Items Lists, which identify life limiting components and major failure modes. Design activities are focused on the elimination of these items before product introduction.

The adoption of a design for reliability approach means focusing early design and test activities on finding and eliminating failure modes and their root causes. Cymer conducts thermal surveys to characterize performance, accelerated step stress thermal testing to measure the limits of operation and find destruct limits, precipitation screens of components utilizing combine thermal cycling and vibration; and life demonstration testing. The overall approach is to extend the operating and destruct limits well beyond expected product operational life.

To date, Cymer has completed FTA analysis of its ELS-6000 laser system and Monte Carlo modeling of design approaches is continuing. Developing and refining the prediction method and failure effects is ongoing. FMEA analysis database is extracted from the FTA models to further delineate the causes and design corrective actions to eliminate failures. Failure analysis of test and manufacturing components is conducted and entered into the FMEA database and design activities tracked until the root causes are minimized or eliminated. Laser and module thermal surveys have been conducted, precipitation screens begun, operating limits are being characterized, and accelerated step stress testing has been successfully applied to Cymer's 5010 design of its pulse power modules.

From system faults trees, the Orion calculated MTBF is 640 hours. System Inherent Design Availability at system maturity is calculated to be 99.5% while overall Operational Availability, including refills and other preventive tasks, is calculated to be 98.2%. These values are based on predictions made from the fault tree analysis of the Orion system. These values compare favorably to early reliability life studies conducted on our 5000 laser. From the data collected, the early 5000 showed an Inherent Design Availability of 98.8% and Operational Availability of 97.8%.

## 5. LASER COMPLIANCE

Cymer's 2000 Hz ELS-6000 laser was designed with an acute awareness of the increased role that safety and regulatory compliance plays in the modern semiconductor manufacturing environment. After establishing the "state of the art" for excimer laser safety and regulatory compliance through the ELS-5000 series of products, the next generation laser incorporates refinements in the approach and implementation of essential features providing greater conformance to international standards and parity with industry expectations. Enhancements in areas of process monitoring, service safety, and electromagnetic compatibility contributed to an expedient evaluation and approval process covering domestic regulatory requirements, semiconductor industry guidelines, and international standards.

Since the early Cymer breakthroughs of digitally controlled laser systems, a "layered" approach has been used to ensure protection of personnel, facilities, equipment, and product. This approach remains valid and is utilized in the latest designs as well. At the top level, the sophisticated control system monitors temperatures, pressures, and flow rates of process resources. Quickly reacting to abnormal conditions the control system can correct process deviations automatically or prevent further operation of a subsystem that is performing outside of defined specifications. Subsystem controls represent the second level of protection provided by the system. Embedded controllers, fail-safe components, and dedicated hardware features can remove source energy in the event of a subsystem fault. Finally, a dedicated and uncompromising hardware-based interlock system decisively inhibits subsystem and system operation in response to the detection of potentially hazardous conditions. At each layer these features have been enhanced and expanded to better mitigate the risks inherent to the laser component of the microlithography process.

The opportunity to improve service personnel safety exists with increased access to modules that comprise the system and the addition of onboard hazardous energy control features. A continued emphasis on modularity along with greater use of connectorization both contribute to reduced exposure to sources and signals during service operations. Lock-out capability for all facility resources is provided along with basic procedures for interrupting hazardous energy sources prior to service/maintenance activities. These are required features to comply with Occupational Safety and Health Agency (OSHA) regulation. A by-product of this implementation is reduced impact on critical facility sources during service procedures as a result of the isolation feature. Ultimately these improvements support increased safety and reduced difficulty of service for the ELS-6000.

Electromagnetic Compatibility (EMC) continues to gain recognition as a challenge in the semiconductor capital equipment environment. This trend is driven both by the European EMC Directive and by the proliferation of high-speed control electronics. The general concern for Electromagnetic Interference (EMI) generated by equipment as well as equipment susceptibility to EMI is an effect on reliability that is very difficult to quantify. Accounting for EMI emissions and immunity requirements early in the design of the ELS-6000 allowed Cymer to meet these challenges very successfully with integrated features for EMI control, containment, and protection. A comprehensive test program was executed to ensure the product met the requirements of both domestic and international test standards for industrial equipment. This program included radiated emissions, conducted emissions, electrostatic discharge immunity, radiated electric field immunity, fast transient voltage immunity, surge voltage immunity, and conducted EMI immunity. Compliance with both domestic and international requirements was demonstrated successfully in each case.

The enhancements and refinements presented from a safety and regulatory compliance perspective along with the sound design principles of previous generations of Cymer excimer lasers culminated in a very successful approval and certification cycle for the ELS-6000 product. Fully meeting the requirements of SEMI S2-93A, the overall safety guideline of the semiconductor industry, the ELS-6000 is also in conformance with the safety and electromagnetic compatibility requirements of the European Union CE Mark certification. The resulting product may be sold and utilized without restriction in major industrial markets worldwide.

## 6. SUMMARY

We have successfully developed and life tested a production-ready 2000 Hz excimer laser system to meet the semiconductor industry's need for increased productivity and profitability. In addition to the obvious advantages in throughput due to the increase in repetition rate, the new laser system delivers significant improvements in dose stability, modularity, and cost of operation through increased module lifetimes.

## ACKNOWLEDGEMENTS

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