A Low Cost of Ownership KrF Excimer Laser Using a Novel Pulse Power and Chamber Configuration

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ABSTRACT

A KrF excimer laser using an all solid state Pulse Power Modulator (PPM) has been studied. This PPM configuration replaces the commonly used thyratron switch with a Silicon Controlled Rectifier (SCR) switch combined with a pulse compression-voltage multiplication circuit. Use of this PPM has extended the useful chamber life of a line-narrowed KrF excimer laser from 1.5 billion to 2.5 billion pulses. Broadband KrF laser performance, optimized for mirror based scanner systems, has also been investigated. A minimum broadband chamber life of 5 billion pulses has been demonstrated with this solid state PPM. While a thyratron-based PPM exhibits an expected lifetime of 3 billion pulses, the solid state PPM used in these experiments has been operated for greater than 6 billion pulses without any decrease in performance. Since 72% of the replacement parts cost for the ELS-4000D line-narrowed excimer laser is due to periodic chamber and PPM replacement, significant cost of ownership reduction is realized by extending the lifetime of the chamber and the PPM.

1. INTRODUCTION

Since deep-UV lithography was first demonstrated using KrF excimer lasers,[1,2] the performance and reliability of these deep-UV light sources have continuously improved. Current laser models from several vendors satisfy the optical specification and uptime requirements necessary for pilot integrated circuit production. Attention has now been focused on the Cost of Ownership (CoO) for these laser light sources. Both line-narrowed KrF lasers for stepper/scanner systems and broadband KrF lasers for scanner systems must achieve reductions in CoO in order to compete on a cost basis with I-line steppers using phase shifting masks or exotic illumination schemes.

The replacement parts cost for the ELS-4000D line-narrowed excimer laser manufactured by Cymer Laser Technologies can be separated into the components shown in the following table:

ELS-4000D Replacement Parts Costs

Component	Percent of Total
Laser Chamber	55%
Pulse Power Module	17%
Line-narrowing Package	11%
Wavemeter	3%
Chamber Windows	6%
Other Optics	8%

The laser chamber and the Pulse Power Module (PPM) account for 72% of the total replacement parts cost. Efforts to increase the lifetimes of these two components will have the greatest impact on the laser's total CoO. Since the broadband KrF laser used in scanner systems will not require a line-narrowing package or wavemeter, the percentage of the total replacement parts cost due to chamber and PPM replacement is even higher at approximately 84%.

The traditional approach to improving chamber or PPM life is by increasing the efficiency (output laser energy/input electrical energy) of the laser. This is done by optimizing gas, mixture, gas pressure and electrode profiles and the laser's pulse power circuit. The increased efficiency reduces the energy loading into the laser, which reduces wear on the laser chamber and PPM. Most broadband lasers, used for micro-machining applications, operate with an efficiency of 3 to 4% with an energy loading of 16-20 J/l-atm of laser gas. In such applications, the requirements for beam properties are not critical. For microlithography, optimization of the laser chamber and PPM can proceed only if the numerous beam properties such as bandwidth, beam size,

0-8194-1788-2/95/$6.00

coherence and pulse-to-pulse stability are simultaneously satisfied. Lasers used in microlithography operate at an efficiency on only 0.4% to 1.25% with similar energy loading (16-20 J/l-atm).

The following sections of this paper describe the results of efforts to increase the lifetimes for both the chamber and the PPM. The chamber's construction materials have been modified for improved fluorine compatibility and the chamber windows have been redesigned for reduced optical loss. The PPM has been completely redesigned to eliminate the use of a high voltage (20kV) thyratron switch. A solid state Silicon Controlled Rectifier (SCR) switch combined with a pulse compression circuit is used in place of the thyratron. Each of these modifications has increased the expected lifetime of both the laser chamber and the PPM.

2. SOLID STATE PULSE POWER OPERATION

The operation of a Solid State Pulse Power Module (SSPPM) can best be described in comparison to the operation of a thyratron based PPM. A thyratron based PPM circuit, shown in Fig. 1, consists of a high voltage power supply, a DC storage capacitor (C_0), a DC charging inductor, a thyratron switch, and a peaking capacitor (C_p). During normal operation, the power supply charges C_0 to 12-20kV through the DC charging inductor in approximately 1ms. When the thyratron is triggered, the charge stored on C_0 is transferred to C_p in approximately 100-150ns. The voltage across C_p also exists across the chamber electrodes and rises until discharge break-down occurs in the laser gas. Upon laser gas breakdown, the energy stored in C_p is transferred to the laser chamber. A typical voltage waveform on C_p is shown in Fig. 2. The initial negative slope reflects the transfer of energy from C_0 to C_p. The much faster positive slope represents the flow of energy from C_p to the laser chamber. The portion of this slope that is above ground potential is caused by inductive overshoot.

Imperfect power transfer from the PPM to the laser gas results in the ringing shown in Fig. 2. The ringing appears after the termination of the laser pulse, therefore; the energy contained in this ringing is wasted. During the ringing, the discharge between the electrodes deteriorates into constricted arcs, resulting in areas of high energy density[3]. Under certain conditions of gas mixture, gas pressure, and operating voltage, this ringing can be reduced. However, as the chamber ages or the gas mixture changes, the operating voltage changes significantly and the effects of the ringing energy become pronounced.

The solid state PPM circuit developed for these experiments is shown in Fig. 3. The 20kV power supply used in the thyratron system is replaced by a 1kV supply. The thyratron switch is replaced by an SCR switch that does not feed C_p directly, but instead switches the energy of C_0 into a pulse compression circuit formed by C_1, C_2, C_3, a step-up transformer, and three saturable inductors[4,5]. The operation of this circuit is as follows. The DC charge stored on C_0 is switched through the SCR and the inductor L_0 into C_1. The saturable inductor, L_1, holds off the voltage on C_1 for approximately 2.5µs and then becomes conducting, allowing the transfer of charge from C_1 to C_2. The second saturable inductor, L_2, holds off the voltage on C_2 for approximately 500ns and then allows the charge on C_2 to flow through the primary of 1:20 step-up transformer. The output from the step-up transformer is stored on C_3 until the saturable inductor L_3 becomes conducting in approximately 100-150ns. The charge is then finally transferred through L_3 into C_p and laser discharge occurs. The voltage waveform on C_p, shown in Fig. 4, closely matches the shape of that produced by the thyratron PPM, except that the SSPPM waveform exhibits little or no after-ringing.

The increased complexity of the SSPPM is compensated for by the elimination of the expensive and short-lived thyratron. An additional and important feature of the SSPPM is the recovery of the energy reflected from the laser chamber. With the SSPPM, the energy reflected by the laser chamber due to impedance mismatch no longer rings back and forth between the PPM and the laser chamber. The SSPPM circuit is designed to transmit this reflected energy all the way back through the pulse forming network into C_0. Upon recovery of this energy onto C_0, the SCR switches off ensuring that this captured energy remains on C_0. Thus, regardless of the operating voltage, gas mixture, or chamber conditions, the voltage waveform across the laser electrodes exhibits the behavior of a well-tuned system. This performance is maintained over all laser operating conditions. Section 4 of this paper will describe the impact on laser chamber lifetime due to this feature of the SSPPM.

3. DIRECT IMPACT ON COST OF OWNERSHIP DUE TO THE SOLID STATE PPM

As shown in the previous section, thyratron based PPMs are simple in design and construction. The lifetime of the thyratron limits the expected lifetime of the entire PPM. If the cost of the thyratron was a small portion of the total PPM cost, then periodic replacement of the thyratron, though inconvenient, would not greatly impact the laser's CoO. Unfortunately, the thyratron used in the ELS-4000D represents 60% of the total PPM cost.

The expected lifetime of the thyratron used in the ELS-4000D is 3 billion pulses. The major life-limiting mechanism is erosion of the thyratron's cathode and anode material[6]. The most obvious effect of cathode erosion is a decrease of thyratron switching efficiency. With age, more of the energy stored in the PPM's DC capacitor is lost in the thyratron. This loss of PPM efficiency leads to ever higher operating voltages, further stressing the thyratron, until eventually replacement is necessary.

A more subtle problem related to thyratron electrode erosion is thyratron prefires. The eroded anode severely reduces the thyratron's high voltage hold-off ability. The thyratron does not completely fail under these conditions but instead exhibits occasional prefires. A prefire event is characterized by premature transfer of energy from C_0 to C_p. Most often a pre-fire occurs before C_0 is fully charged, leading to a premature and weak laser pulse.

Missed laser pulses are easily handled by a stepper system that integrates the dose incident on the wafer. If a laser pulse is missed, the stepper can detect this and request an additional laser pulse. Scanner systems, with their continuously moving exposure field, can not easily compensate for a missed laser pulse. Scanner throughput considerations lead to exposure strategies that use as few laser pulses per sub-scan region as possible. A typical number of laser pulses per sub-region is 50 or less. Missing just one laser pulse could lead to a dose error of 2% or greater. An exposure sub-region with an illumination shape other than rectangular will place even greater importance on a select few pulses, increasing the detrimental effect of a missed pulse. Like a stepper, a scanner could monitor each laser pulse and determine if a missed pulse occurred. The wafer could then be reworked if the loss of the single effected die was deemed unacceptable.

The SCR switch used in the SSPPM does not suffer from gradual degradation nor does it exhibit pre-fire behavior. This same technology has been demonstrated to last for greater than 30 billion pulses elsewhere under similar conditions without a single missed pulse or PPM failure[5,7]. The prototype SSPPM used in these experiments has so far accumulated in excess of 6 billion pulses without a single failure. By monitoring the stored energy in C_0 required for nominal operation we can determine if the SSPPM efficiency has degraded with age. Within experimental error, this SSPPM exhibits the same electrical efficiency at 5 billion pulses as it did at zero pulses.

There are three factors that lead to a reduced overall system CoO when using a SSPPM in place of a thyratron based PPM. The most significant reduction in CoO is the ten times increase in expected lifetime from 3 billion pulses for a thyratron PPM to 30 billion pulses for a solid state PPM. The second factor in overall system CoO reduction is the complete elimination of missed laser pulses resulting in a reduction in wafer level rework. The third factor in CoO reduction involves down time for a laser service procedure. The thyratron based PPM used on the ELS-4000D must go through a 10 minute warm-up period to achieve proper thyratron temperature. The SSPPM requires no warm-up time, and thus each laser service procedure can be shortened by approximately 10 minutes.

4. INDIRECT IMPACT ON COST OF OWNERSHIP DUE TO SOLID STATE PPM (EXTENDED CHAMBER LIFE)

The after-ringing described in Section 2 has been found to have a detrimental impact on the laser chamber's electrode lifetime. After the main laser discharge, current flow between the chamber electrodes becomes non uniform and breaks up into localized areas of high current density called streamers[3]. We have correlated the local density of these streamers with increased electrode erosion and have found that the regions of electrode that exhibit the greatest density of streamers also suffer the greatest amount of electrode erosion. It has been hypothesized that these streamers last longer than the main discharge and are the primary current path for the after-ringing energy shown the voltage waveshape of Fig. 2 (produced by a thyratron PPM). Elimination of this after-ringing will starve the streamers of energy and reduce the amount of electrode damage caused by these streamers.

The SSPPM described in Section 3 reduces the amount of energy in the after-ringing portion of the chamber voltage waveform. This reduction is made evident by comparing the thyratron PPM waveform shown in Fig. 2 and the SSPPM waveform shown in Fig. 4. A clear reduction in the after-ringing is evident. The energy recovery properties of the SSPPM allow us to quantify the amount of energy recaptured by the SSPPM that otherwise would have participated in streamer formation. The voltage on C_0 after the SCR has switched off can be used to measure the amount of recovered energy. Fig. 5 shows the voltage waveform on C_0 before and after a laser pulse. The initial stored energy calculated by $E_0 = 1/2 C_0 V_0^2$ is 3.5J and the recovered energy is .12J.

The recovered energy, though a small fraction of the initial (3.4%), is energy that would have fed streamers and subsequently contributed to erosion of electrode material.

Measuring electrode erosion rates over short periods is a difficult task. We have found that one reliable method is to monitor the consumption of fluorine during laser operation. If a chamber is completely passivated, its rate of fluorine consumption is low when the laser is not firing, on the order of 0.0002kPa of F_2 per hour. When the laser is operating at 500Hz rep rate, the F_2 consumption rate is approximately 0.025kPa per hour or 0.014kPa per million pulses. It is thought that most of the increased consumption rate during laser operation is due to electrode erosion that continuously exposes fresh, unpassivated electrode material to the laser gas. Thus, changes in the F_2 consumption rate during continuous operation can be used as a relative measure of electrode erosion.

The F_2 consumption rates for the thyratron PPM and the SSPPM have been compared using the same laser chamber. Fig. 6 shows the operating voltage for both the thyratron PPM and the SSPPM during continuous operation. As the F_2 is consumed, the operating voltage must increase to make up for lost lasing efficiency. The F_2 injection algorithm used in the ELS-4000D monitors the operating voltage and will perform an F_2 injection after a certain rise in operating voltage. The parameters for this experiment were 0.05kPa of F_2 per injection and a 400V increase in operating voltage between injections. As shown in Fig. 6, the thyratron PPM averaged 3.6 million pulses between injections or an F_2 consumption rate of 0.0137 kPa/Mpulse. In contrast, the SSPPM averaged 5.9 million pulses between injections or 0.0084kPa/Mpulse. Use of the SSPPM results in a 40% reduction in F_2 consumption. It is difficult to convert this 40% reduction in F_2 consumption rate directly into a percentage reduction in electrode erosion except to say that a significant reduction is expected and thus a measurable increase in chamber life is predicted.

To verify that the chamber life is extended by use of the SSPPM, we began a life test of an ELS-4000D line-narrowed laser equipped with the SSPPM described in Sections 2 and 3. For comparison, the results of a life test using a thyratron based PPM are shown in Fig. 7 which is a plot of operating voltage versus the number of pulses on the laser chamber. Each data point represents the operating voltage at the midpoint of a gas fill. Each gas fill lasted for approximately 35 million pulses. After 1.5 billion pulses the operating voltage exceeded 15kV. The limit of 15kV operating voltage is used by Cymer as a definition of the end of chamber life.

The SSPPM life test results are shown in Fig. 8 (similar to Fig. 7) of operating voltage versus the number of pulses on the laser chamber. It should be noted that the Y-axis of this plot still covers the range between 10kV and 15kV even though the SSPPM operating voltage is less than 1kV. The voltage values for the SSPPM have been multiplied by a factor so that the laser control system and all the plots in this paper will have the same scale when comparing thyratron and SSPPM performance. This factor was found by first setting the thyratron PPM to 13kV operation and measuring the voltage on C_p. Then the laser was converted to SSPPM operation and the voltage on C_0 was adjusted so that the voltage on C_p was the same as that produced by the thyratron based PPM. A calibration factor was then chosen so that the laser's control system considered this C_0 voltage as 13kV. The actual operating voltage on C_0 for the SSPPM was approximately 700V.

As Fig. 8 shows, the SSPPM extended the chamber life to 2.5 billion pulses, a 1 billion pulse increase over the thyratron based lifetest. This increase in chamber life should have a dramatic impact on the CoO of the ELS-4000D line-narrowed KrF laser. The order in which these two lifetests were performed may have understated the improvement brought about by the SSPPM. The thyratron based lifetest was performed first, and all the same cavity optics were reused for the SSPPM lifetest. Most critical of these optics is the line-narrowing package. The expected lifetime of the ELS-4000D line-narrowing package is 3 billion pulses. The line-narrowing package used in these experiments accumulated 1.5 billion pulses during the thyratron based lifetest and then an additional 2.5 billion pulses during the SSPPM lifetest, for a total of 4 billion pulses. At the end of the SSPPM lifetest, the efficiency of the line-narrowing package was compared to that of a new package. The old line-narrowing package was found to cause a 700V increase in operating voltage compared to a new package. This 700V loss of operating efficiency caused the SSPPM to deposit more energy per pulse into the laser chamber. The effect on operating voltage with a new line-narrowing package and redesigned chamber windows is shown in Fig. 8. Almost half of the 1.5kV reduction in operating voltage is due to a new line-narrowing package, and the other half is due to redesigned chamber windows. The redesign of the chamber windows is described in the next section.

After completing the 2.5 billion pulse lifetest, this chamber was used for further SSPPM development. The chamber accumulated an additional 1.4 billion pulses during this period, in line-narrowed configuration as well as broadband configuration. We then began a broadband chamber lifetest with SSPPM starting with a total chamber pulse count of 3.9 billion pulses. The chamber was operated at 500Hz/30mj per pulse for an average 248nm output power of 15W. The results of this lifetest are shown in Fig. 9. Again, operating voltage versus chamber pulse count is plotted, but this time we did not perform a gas exchange after every 35 million pulses. Only 5 gas refills were used in this lifetest. The first gas fill lasted for 350 million pulses before the operating voltage reached the 15kV limit. The remaining gas fills were exchanged after approximately 250 million pulses each. During this lifetest, the pulse count on the chamber increased from 3.9 billion to 5.3 billion.

No chamber window exchange or cleaning was performed during the broadband lifetest. The chamber windows were cleaned at a chamber pulse count of 3.6 billion pulses and were not inspected or cleaned until 5.3 billion pulses. The reduced electrode erosion afforded by the SSPPM has also reduced the buildup of dust on the chamber windows. The typical chamber window cleaning interval for the ELS-4000D is 300 million pulses. This lifetest demonstrates a chamber window cleaning interval in excess of 1.5 billion pulses. The next section describes how we took advantage of reduced dust buildup in redesigning the chamber windows.

As the results in this section show, the SSPPM has extended the useful chamber life for a line-narrowed KrF excimer laser from 1.5 billion pulses to 2.5 billion pulses and demonstrated a broadband chamber life of 5 billion pulses. Use of the SSPPM has also demonstrated an increased chamber window cleaning interval from 300 million to 1.5 billion pulses.

5. IMPROVEMENTS IN CHAMBER DESIGN FOR REDUCED CoO

The chamber design has also undergone several improvements to reduce the laser's CoO. The gas life has been extended by replacing virtually all the organic materials inside the chamber with metal or ceramic. The seals used in the chamber's pressure vessel represent the largest surface area of exposed organic material. Until recently, these seals were made with an elastimer type material. This material is not completely fluorine compatible. Over a gas fill, the fluorine would be lost to chemical reactions with the seal material. These elastimer seals have been replaced with metal seals. The first gas fill shown in the broadband lifetest (Fig. 9) demonstrates a single fill gas life of 350 million pulses or 8 days of continuous 500Hz operation. This lower rate of gas consumption leads to reduced costs for laser gas and increased system uptime due to fewer interruptions for gas fills.

The second important chamber design improvement is the implementation of Brewster windows. Brewster windows have not been implemented in the past due to their increased sensitivity to scattering by dust particles. The increased chamber window cleaning internals described in Section 4 have made the conversion to Brewster chamber windows practical. The term Brewster windows in this case is not entirely correct since the chamber windows are not held at exactly Brewster's angle (55.7° for CaF_2). Constraints of mechanical fit and practical window optic size led to a choice of 47° for the chamber windows. At 47°, the single surface reflection in air for CaF_2 is 0.52% (99.48% transmission) compared to 3.62% (96.38% transmission) for normal incidence. Since there are two chamber windows and both are traversed twice per cavity round-trip, the window's single surface transmission is taken to the 8th power to find the chamber's round-trip transmission. The normal incidence chamber window configuration has a round-trip transmission of 74.4% and the Brewster window configuration has a transmission of 95.9%. Converting to the Brewster window configuration leads to a 21.5% reduction in round-trip optical cavity losses caused by the chamber windows.

One cannot expect a 21.5% increase in overall efficiency since other factors contribute to the total round-trip optical cavity loss. Upon completion of the 2.5 billion pulse line-narrowed lifetest shown in Fig. 8, the line-narrowing package was replaced and the chamber windows were converted to the Brewster design. The total effect on operating voltage was a 1.5kV reduction. The drop in operating voltage attributed to the windows alone was found to be 0.8kV. This 0.8kV drop in operation voltage corresponds to an 11% relative increase in laser efficiency.

7. CONCLUSIONS

These experiments show that an all solid state pulse power modulator combined with an advanced chamber design can lead to a dramatic reduction in cost of ownership for both line-narrowed and broadband KrF excimer lasers. A line-narrowed chamber life of 2.5 billion pulses and a broadband chamber life in excess of 5 billion pulses have been demonstrated. To date, the prototype solid state PPM used in these experiments has accumulated more than 6 billion pulses without a single failure or degradation in performance.

8. REFERENCES

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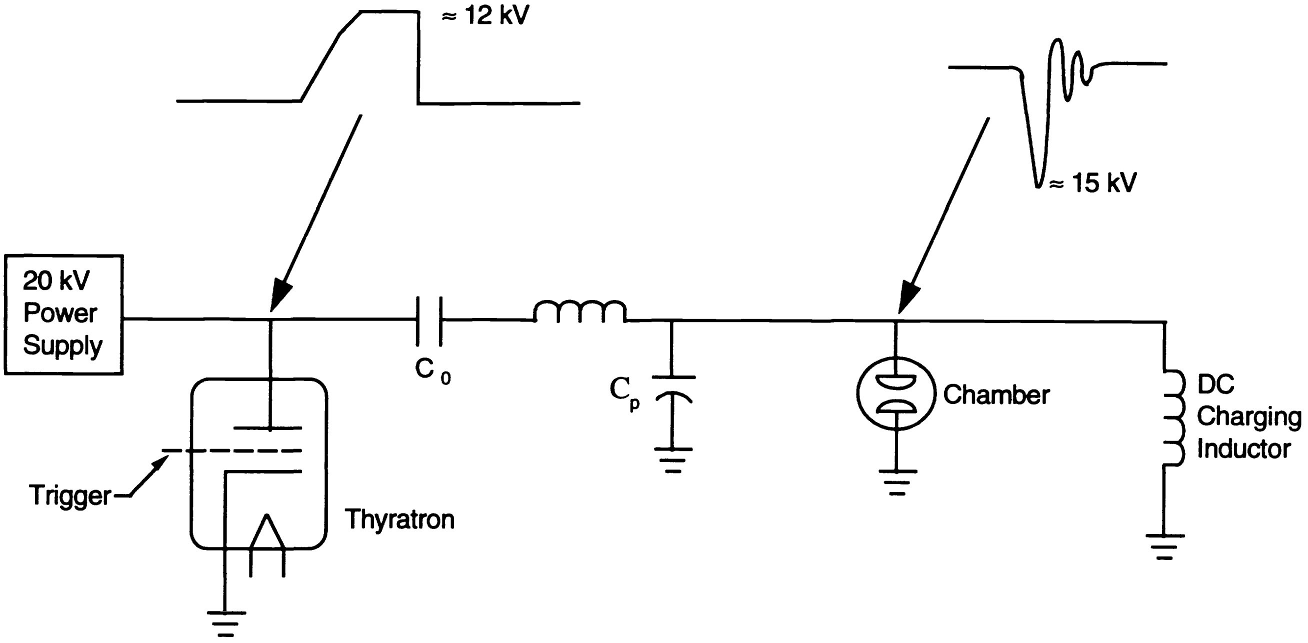

Fig. 1. Simplified electrical schematic of a thyratron based pulse power circuit used for KrF excimer lasers.

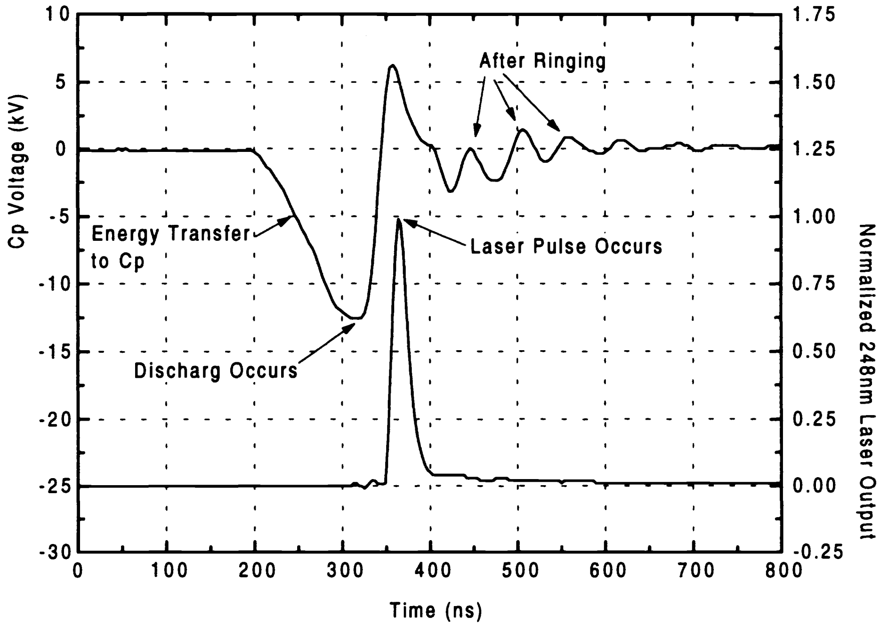

Fig. 2. Measured voltage waveform on C_p produced by the thyratron based pulse power circuit shown in Fig. 2.

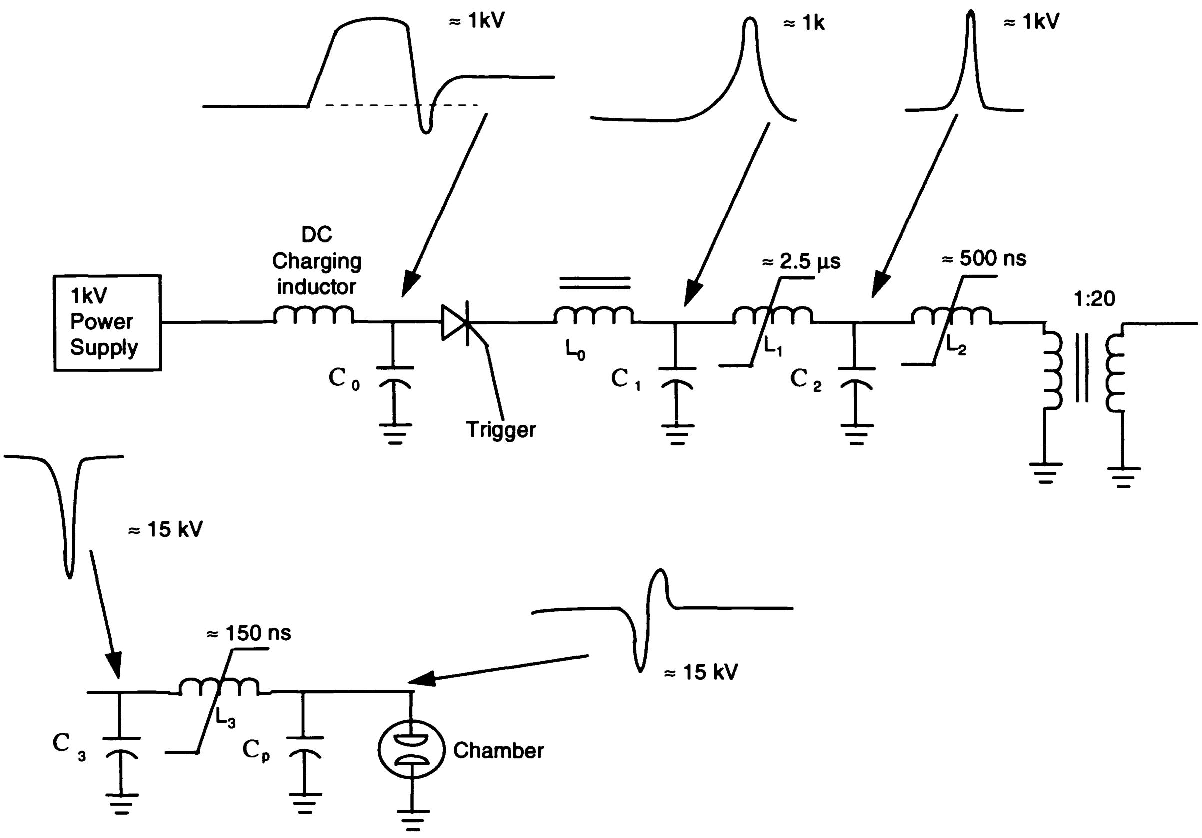

Fig. 3. Simplified electrical schematic of the solid state pulse power circuit developed for use with KrF excimer lasers.

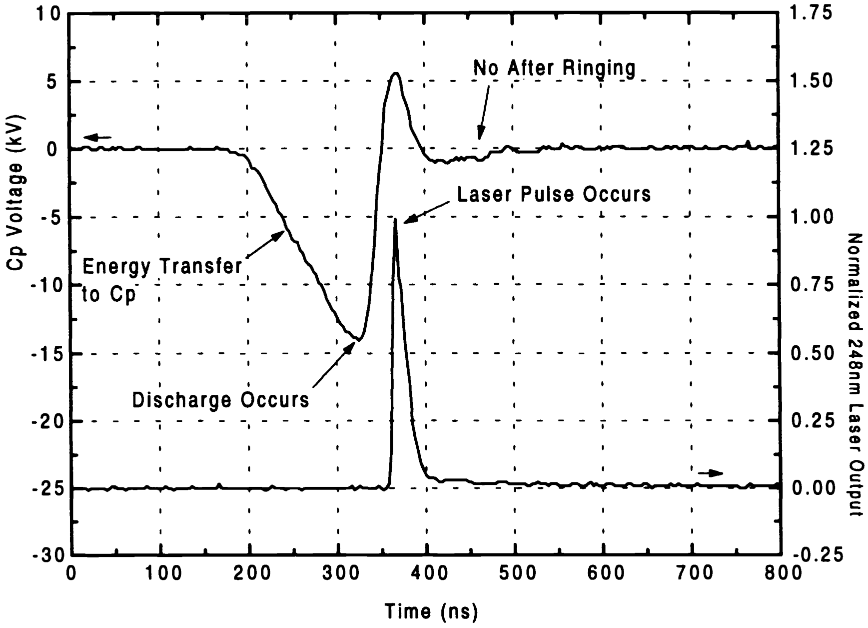

Fig. 4. Measured voltage waveform on C_p produced by the solid state pulse power circuit shown in Fig. 3.

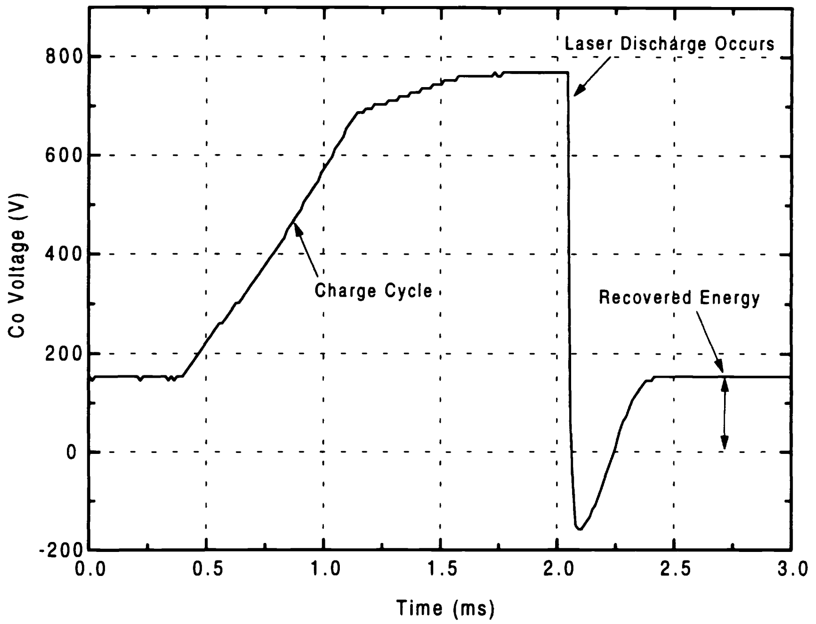

Fig. 5. Measured voltage on C_0 before and after laser discharge, showing the energy recovered by the SSPPM.

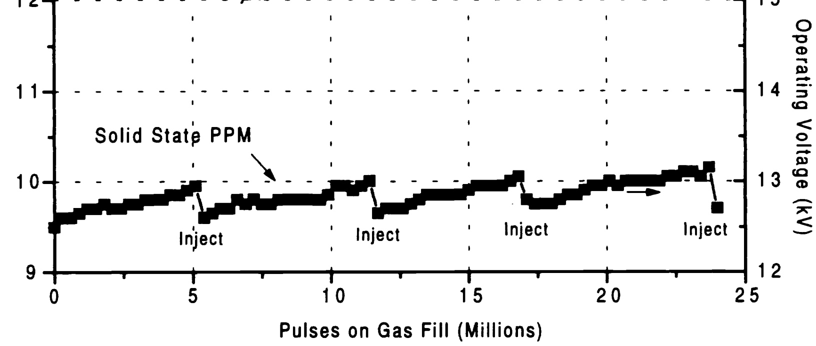

Fig. 6. Measured operating voltage for thyratron PPM and SSPPM, showing reduced F_2 consumption with SSPPM.

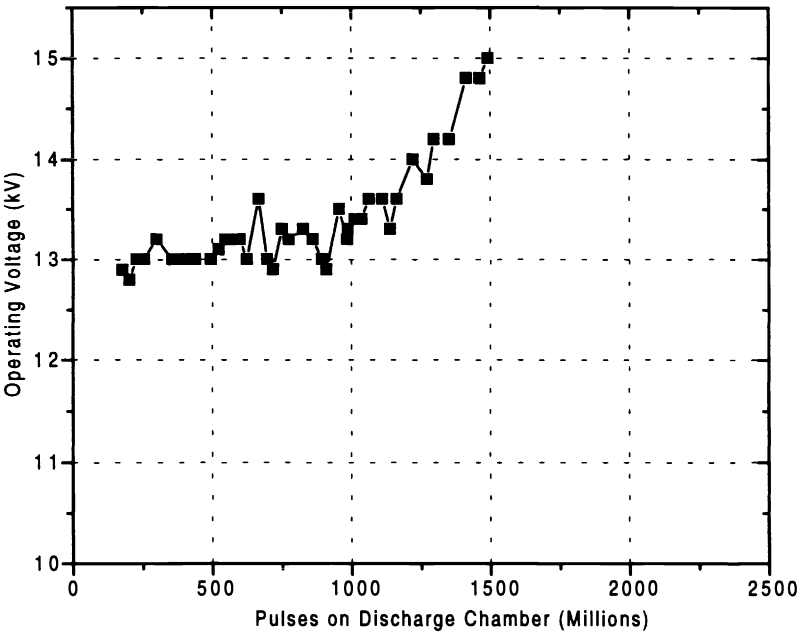

Fig. 7. Measured operating voltage vs. pulse count with a thyratron based PPM, showing a 1.5 billion pulse chamber life (line-narrowed configuration).

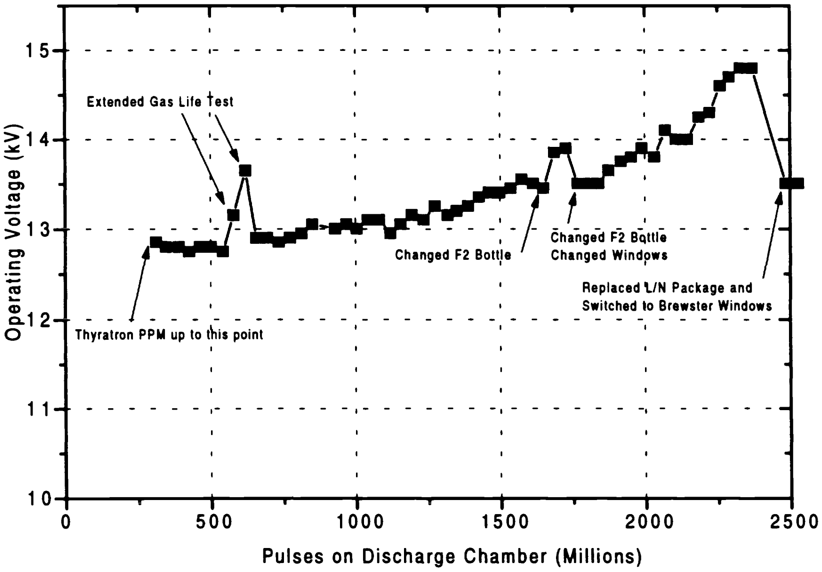

Fig. 8. Measured operating voltage vs. pulse count with a SSPPM, showing a 2.5 billion pulse chamber life (line-narrowed configuration). Also shown is the reduction in operation voltage with a new line-narrowing package and redesigned chamber windows.

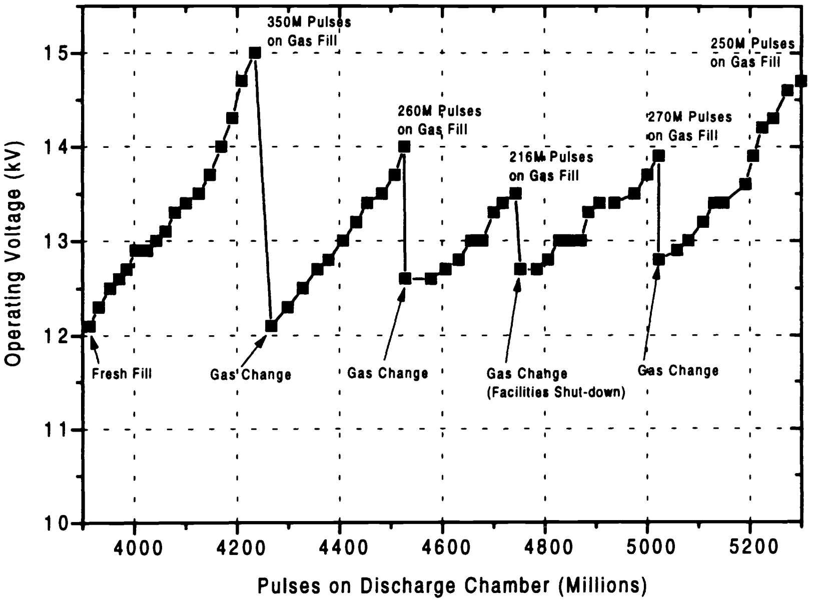

Fig. 9 Measured operating voltage vs. pulse count with SSPPM (chamber configured for broad-band operation), demonstrating a broadband chamber life in excess of 5 billion pulses. Also demonstrating a window cleaning interval greater than 1.5 billion pulses.