COMPARISON OF COMMONLY USED EXCIMER LASER PULSED POWER CIRCUITRY

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Introduction

This paper compares the electrical characteristics of the various types of pulsed power circuits commonly used in commercial excimer lasers. Sixty watt commercial krypton fluoride lasers are used as the test cases, however the lasers are multigas devices operating on all the usual excimer transitions. Circuit measurements made on these lasers are presented and energy and charge transfer through the systems are discussed and analyzed. Subsequently these circuits are discussed with regard to more recent circuit techniques to assess design approaches for higher power excimer lasers.

Laser Circuits and Measurements

Of the various circuit configurations used in commercial excimer lasers the two most common are the pulse charged capacitor scheme and the LC inversion circuit with full magnetic switch. One of the lasers tested employs the simple pulse charged circuit (PC) utilized by two of the major commercial manufacturers. The other laser employs the more complex LC inversion circuit with a magnetic switch in the output stage of the inversion circuit. This circuit will be referred to as the MS circuit. The two circuits are shown in Figure 1*. Values of the capacitors shown in the circuit are the actual values measured for the lasers tested.

In Figure 2 are shown current pulses passing through the thyratron switch at the point when the lasers are emitting comparable 400 mJ pulse energies on the KrF wavelength. It can be seen that the peak current through the thyratron in the PC circuit is about half that being transferred through the MS circuit. Although only half of the stored charge in the MS circuit is transferred through the thyratron, the dI/dt is comparable in both cases, being of the order of 10^{11} AS^{-1}. Since dI/dt is one of the determinants of thyratron life neither circuit offers a particular advantage in this regard.

However, since both the peak current and the pulse width are greater in the MS circuit, the integrated charge ($\int Idt$) is also several times larger than in the case of the PC circuit. Consequently the thyratron in the MS circuit should be of a higher current rating than the one in the PC circuit. In addition the tube in the MS circuit must be oil cooled whereas forced air cooling is sufficient for the PC circuit. Moreover the current pulse in the MS circuit has a significant amount of current reversal. This current reversal, at a normal operating voltage of 23 kV, can continue for microseconds. The substantial level of current reversal necessitates use of a hollow anode thyratron. The tube used in the MS circuit (EEV C1573C) performs its job admirably under such adverse conditions and

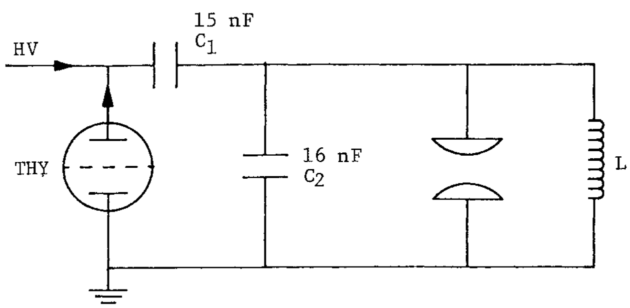


FIGURE 1(A). PULSE CHARGE (PC) CIRCUIT. THYRATRON IS EGG-HY3204 NORMAL ANODE GROUNDED CATHODE. C_1 SINGLE OIL FILLED CAPACITOR, C_2 CERAMIC ARRAY.

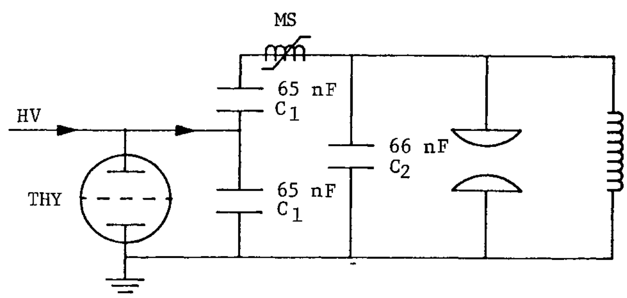


FIGURE 1(B). LC INVERSION CIRCUIT WITH MAGNETIC SWITCH (MS CIRCUIT). THYRATRON EEV-CX1573C (HOLLOW ANODE). C_1, C_2 CERAMIC CAPACITOR ARRAYS.

In the experiments reported here, voltage measurements were made with Tektronix P6015 high voltage probes and Gen Tec 100 kV probes. Current measurements were made with several Pearson 110A current probes, T & M current viewing resistors and dI/dt probes. Oscilloscopes used for the measurements were Tektronix model 7844's. Laser output energy was measured with Scientech calorimeters. The charge transfer and stored energy measurements take into account the different types of ceramic capacitor material used in the laser circuits.

clearly shows the efficacy of the hollow anode design. Minimal levels of current ringing in the PC circuit conversely allow the use of a simple standard anode tube (EG&G HY3204). It can clearly be seen that despite the implied advantages of the MS circuit in regards to reduced thyratron loading, in reality the MS circuit places much more stringent demands on the thyratron than the PC circuit.

*PREION CIRCUIT OMITTED FOR CLARITY

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1987	**N/A**	**-**

4. TITLE AND SUBTITLE	
Comparison Of Commonly Used Excimer Laser Pulsed Power Circuitry	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Lumonics Inc., 105 Schneider Road, Kanata, Ontario K2K 1Y3**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

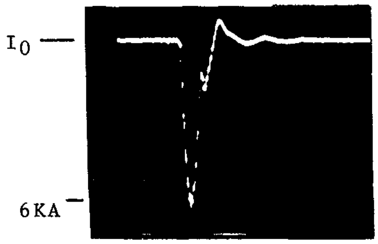
13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

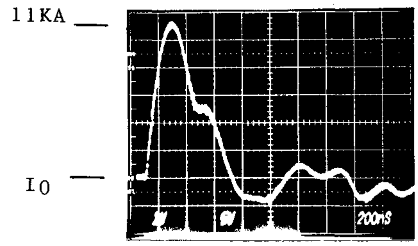
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18



PC CIRCUIT AT 36KV DC.
TUBE CURRENT, 1 KA/DIV, 200nS/DIV.



MS CIRCUIT AT 23KV DC.
TUBE CURRENT, 2 KA/DIV, 200 nS/DIV.

FIGURE 2. CURRENT THROUGH THE THYRATRON FOR PC & MS CIRCUIT AT TYPICAL OPERATING VOLTAGES. OPERATION ON KrF WITH OUTPUT PULSE ENERGY 400 mJ.

Comparison of the currents, stored energy, charge and efficiency of the two lasers at various points in the circuits is detailed in Table 1. In the MS circuit the majority of the energy loss occurs during the initial part of the LC inversion process up to the firing of the magnetic switch. About 40% of the initial stored energy has been lost by the time the magnetic switch has fired. This amounts to 2 K watts at 150 Hz, and explains the need for oil cooling of both the thyratron and the magnetic switch. It is also interesting to note that the energy lost up to this point in the MS circuit is greater than that used in total in the PC circuit. After the magnetic switch the energy transfer efficiency is good and about 52% of the initial stored energy ends up in the peaking capacitors (C_2) associated with the discharge. This is comparable to the PC circuit where 56% of the stored energy ends up in the peaking capacitors.

Comparing the initial DC stored energy (J) to the optical output energy (in mJ) for KrF we find that the overall PC circuit efficiency is close to 4% while the MS circuit is about 1.2%. One difference apart from electrode circuit loop speed is that the PC laser uses neon diluent while the MS laser uses helium. However even when the PC device is operated with a helium diluent it achieves efficiencies of approximately 3% and so is still more than twice as efficient.

From the charge transfer data in Table 1 it can be seen that the MS circuit transfers nearly 4 times the amount of charge stored in the PC circuit into the electrode structure. It is well known from spark gap and other discharge studies that charge transfer is the primary mechanism leading to discharge electrode erosion. Thus although the MS laser electrode is 60% longer than the PC laser electrode there is still about 2.5 times greater charge transfer per unit length than in the PC design.

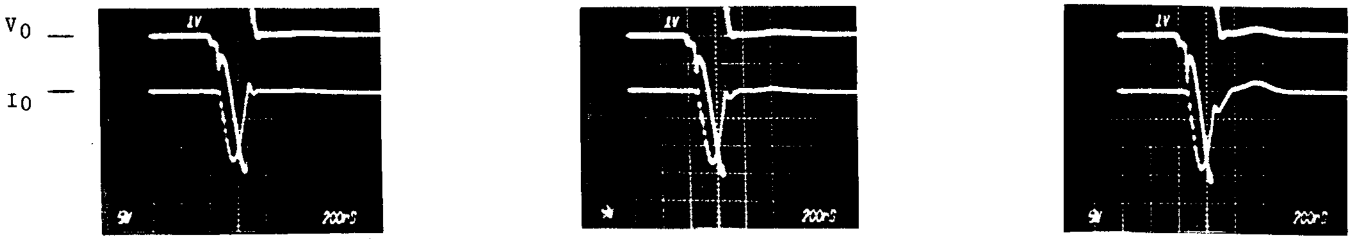
The higher DC operating voltage of the PC circuit could be construed as a slight disadvantage but this merely involves an appropriate increase in spacings. Pulse voltages are actually higher in the MS circuit as shown in Table 1.

In general, apart from possible problems with with MS electrode lifetime, recently published data[1,2] on lifetime achieved by PC and MS circuits indicates that both systems can achieve respectable component running lifetimes approaching 10^9 pulses. An evaluation of the above MS circuit data shows clearly the increasing power loss, component count and design complexity. In addition there is of course some sacrifice of serviceability without seemingly accruing any improvement in reliability or component lifetime over the PC design.

Both circuits are readily capable of achieving 100 watts of ultraviolet output power without overly stressing the basic technology. A PC circuit using a single three inch hollow anode tube (HY3211) with a ferrite magnetic assist produces 40^+ watts on ArF and 100 watts on KrF with about 3 K watts of DC power supply. This is about one third of the power supply required for an MS 100 W laser. In Figure 3 the current through the thyratron and voltage across the electrode structure are shown for three different voltages for this laser when operating at 200 Hz on ArF. It is difficult to maintain this over a range of voltages in the MS circuit, due to the voltage dependent characteristics of the magnetic switch. It can be seen that well damped V,I traces can be readily obtained with PC designs even when operating on the difficult ArF transition. This is important as optical output stabilization techniques usually depend on variation of the DC operating voltage.

Excimer Lasers at Multi-Hundred Watts

The present generation of thyratrons[3,4] with hollow anode and dispenser cathode technology are capable of 500 Hz operation with high peak currents (> 10 KA) and long life (approaching 10^{10} pulses). There seems therefore no clear reason why the PC design approach can not be scaled to achieve output powers, on KrF at least, in excess of 200 watts. Possible problems lie not so much with the pulse power in this regime but with such things as optic damage related to the relatively small (1 cm^2)beam sizes typically produced by current commercial devices. Should efficiency improvements be made for the MS circuit laser then similar powers could also be readily obtained with this design.



32KV, 120mJ   34KV, 157mJ   36KV, 205 mJ

FIGURE 3. CURRENT PULSES FOR 40+W ArF CAPABILITY PC DESIGN LASER (100W KrF) AT THREE DC VOLTAGE SETTINGS. FERRITE MAGNETIC ASSIST ON EGG-HY3211 HOLLOW ANODE TUBE BREAK VOLTAGE (TOP TRACES): 5KV/DIV, TUBE CURRENT (BOTTOM TRACES): 2KA/DIV, 200 nS/DIV.

Methods of increasing beam size while also maintaining reasonably good efficiency seem to be plausible at high optical power levels. In addition it is prudent to lower the stress on the pulse power components when handling tens of kilowatts of electrical power.

Various circuits to isolate the thyratron from large switching transients have been reported, apart from the MS circuit discussed here.[5,6] More elegant approaches have been reported for impedance matching to a pseudo steady state discharge using spiker sustainer circuits.

Unfortunately, this approach has been effective to date only for XeCl. Two formats have been successfully reported to date: the double discharge approach where the PFN is isolated by a secondary discharge integral to the laser vessel[7], and the magnetic switch format where the PFN is isolated from the spike by a saturable magnetic element[8,9].

ITEM	MS LASER	PC LASER
PEAK CURRENT IN TUBE I_p (kA) MEASURED	11	6
RATE-OF-CURRENT, Di/Dt, IN TUBE (kA/μs)	70	80
ENERGY LOSS IN SWITCHING PHASE PER PULSES (mJ)	150	150
ENERGY LOSS IN THYRATRON DURING COMMUTATION PER PULSE (J)	5	<2
PEAK POWER (TUBE) (MW)	>20	<10
WALL PLUG POWER (KW)	7.3	2.6
WALL PLUG EFFICIENCY (%)	0.8	2.3
OPERATING VOLTAGE OF TUBE (kV) TYPICAL	23	35
RMS CURRENT (A) (SINEWAVE ASSUMED)	50	20
CALCULATED POWER FACTOR Π_b	2.5×10^{17}	4×10^{17}
TYPICAL EFFICIENCY (%) (OPT/STD)	1.2	3.8
INITIAL DC STORED ENERGY (J)	35 (23 kV)	10 (37kV)
INTEGRATED CHARGE THROUGH TUBE (INCLUDING RINGING) mC	4	0.6
ELECTRODE BREAK VOLTAGE (MAX) (kV)	33	34
AFTERCURRENT (% 1ST PK)	20-30	10
HOLDOFF VOLTAGE MAGNETIC SWITCH (kV)	38	NO MAG SWITCH
ENERGY STORED IN PULSE CHARGED CAPS (MAX) J	23	6
CHARGE STORED IN PULSE CHARGED CAPS (MAX) mC	1.42	0.38

TABLE 1. MEASUREMENTS OBTAINED WITH LASERS OPERATING ON KrF AT 150 Hz, 400 mJ/PULSE

Efficiencies in excess of 4% have been reported using both of these techniques. For XeCl, this is a marked improvement over those observed in capacitor transfer circuits (2.5%), with the added advantage of greatly reduced switching requirements.

We have examined these circuits at Lumonics for utilization in commercial products. A circuit is shown in Figure 4 for a diode-format magnetic ferrite isolated spiker sustainer operating on XeCl with distributed spark preionization. A pulse energy of 600 mJ was obtained with overall efficiency of 3%. Effective impedance matching was observed at a PFN voltage of 12 kV with sustained discharge voltage of 6 kV. Approximately 20% of the stored energy was utilized for the fast thyratron driven spiker and preion circuit. Alternatively, the modest amount of energy required by a spiker circuit indicates the plausibility of using SCR driven pulser circuitry with 10^{10} shot life expectancy.

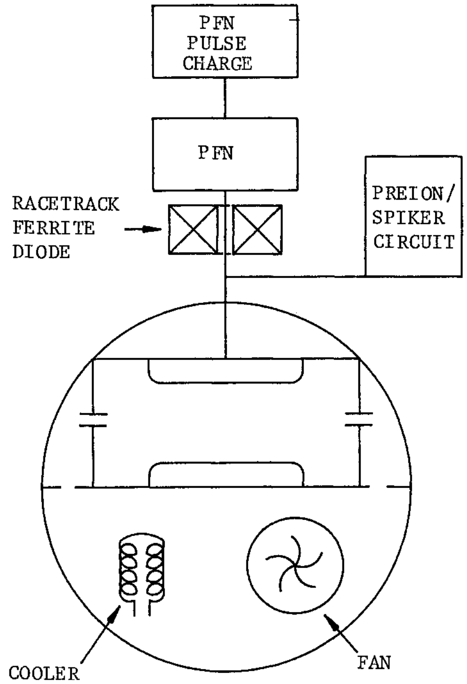


FIGURE 4. SPIKER-SUSTAINER CIRCUIT SCHEMATIC. UNIFORM BEAM XeCl, 3% EFFICIENT, 600 mJ.

Although impedance-matched spiker sustainer circuits have good potential to improve the reliability and duty cycle of excimer lasers, there remain many areas to be investigated before this potential can be fully realized.

Conclusion

In this paper we have clearly shown that for power levels < 100 W, a simple properly designed PC circuit is preferred over a MS circuit on the basis of higher efficiency, lower component count, and reduced complexity. For higher power levels it is inferred that more sophisticated pulse power formats with larger beam cross-sections are likely to be employed.

Acknowledgements

The data quoted in this paper are the results of efforts of the Lumonics R&D and Engineering Groups over a period of several years. The development efforts of the thyratron manufacturers especially EEV for their singular achievements with hollow anode and dispenser cathode technology are gratefully acknowledged.

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