High efficiency XeCl laser with spiker and magnetic isolation

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High efficiency x-ray preionized discharge XeCl laser excitation has been achieved by combining spiker/sustainer excitation techniques with a simple and reliable magnetic isolator. The troublesome rail-gap switch has been eliminated by using the laser discharge itself as the switch. An efficiency of 4% with 2.7 J optical energy was demonstrated.

Conventional preionized discharge XeCl lasers typically operate at efficiencies of 2% or less. The voltage required for rapid breakdown is not consistent with efficient, impedance matched coupling of the electric driver to the laser load. However, efficiencies as high as 4% have been achieved with an electric circuit in which the breakdown and sustaining pulses are provided by separate circuits.[1] In such schemes, the initial high-voltage breakdown pulse is supplied by a high-impedance, low-energy circuit that must be isolated from the low-impedance sustaining circuit. Rail-gap switches have been used previously for this application. However, for long-life, high-repetition-rate lasers, rail gaps have several disadvantages, including electrode erosion, the necessity for flowing gas to give reproducible performance, and conduction losses.

We describe here a different, high efficiency circuit scheme in which a magnetic switch is used to isolate the low-impedance and high-impedance circuits. This scheme, however, requires that the laser gas itself act as a switch in the circuit, holding off the lower voltage, low-impedance circuit. Laser self-switching has been reported by de Witte *et al.*, but the efficiency was low because a separate spiker circuit was not employed.[2]

We report here a 4% efficient XeCl laser using a magnetic isolator. Magnetic isolation is desirable for long-life, high-repetition-rate lasers because magnetic switches are passive elements that have demonstrated long lifetime at high repetition rates for both laser and radar applications. Our approach combines the high efficiency spiker/sustainer excitation technique with a simple and reliable ferrite isolator. The implementation is straightforward and requires no auxiliary circuitry. A similar technique was recently reported by Taylor and Leopold, who used two Metglas-alloy, tape-wound cores in a transformer configuration to both step up the voltage for the spiker pulse and to isolate it from ground.[3] However, the overall efficiency was limited to 2% because the losses in the Metglas-alloy cores required the energy in the spiker circuit to be comparable to that in the sustainer circuit.

Our x-ray preionized XeCl laser used an 8-in.-diam Lucite tube as a pressure vessel. The electrode gap was 3.8 cm and the x-ray source was masked to illuminate an area 3 cm wide by 60 cm long. The aluminum electrodes were contoured simply with a 4-cm flat region in the center and a 2-cm radius on either side. The ground electrode was milled down to a 1.5 mm thickness over a 3×60 cm area to improve x-ray transmission. The laser beam profile recorded on Dupont Dylux proof paper was rectangular and measured 3.8×3.5 cm. This cross-sectional area corresponds to a discharge volume of ≈ 800 cm^3. The laser cell was sealed with antireflection-coated, fused-silica windows that were approximately aligned with the optical cavity. The optical cavity consisted of a 20-m-radius maximum reflector and a flat 20% reflectivity output mirror separated by 1.05 m.

Figure 1 presents a schematic diagram of the electrical circuit for driving the laser. The low-impedance sustainer consisted of eight pulse forming lines (PFL's) connected in parallel, having a $Z \approx 0.2\ \Omega$, $\tau \approx 120$ ns, and a measured $C = 289$ nF. The high-voltage electrodes of the three-conductor, solid-dielectric PFL's were connected together and to the laser head by an aluminum plate surrounded by a race track constructed from ferrite bricks. Low-loss microwave ferrite bricks ($\mu_0 = 54, B_s = 0.3$ T) with good high-frequency characteristics were epoxied together to make a 90-cm-long race track with a total ferrite volume of < 0.01 m^3 for the final configuration.

The spiker consisted of a 6-nF capacitor switched by a triggered spark gap and connected to the laser head by four $Z = 23\ \Omega$ cables. The laser head and transition section had a capacitance of 1.7 nF. For optimum performance, an additional 4 nF of capacitance was added by connecting eight 0.5-nF TDK ceramic capacitors to the transition section between the ferrite race track and the laser electrode. The voltage rise time for the spiker pulse with this capacitance ($C \approx 6$ nF) was ≈ 50 ns and the breakdown voltage was ≈ 40 kV.

The laser energy was measured with a 4-in.-diam surface-absorbing disk calorimeter (Scientech No. 36-0401). Laser efficiency in this letter is defined as the extracted optical energy divided by the sum of the energy stored on the

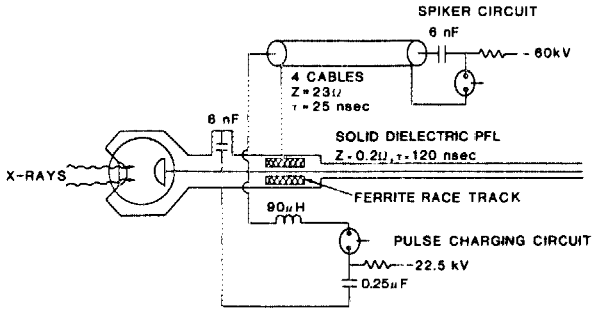

FIG. 1. Schematic diagram of spiker/sustainer excitation circuit with magnetic isolation switch. The magnetic switch is reset by the PFL pulse charging current. For the magnetic diode case, the pulse charging lead is moved to the PFL side of the ferrite race track.

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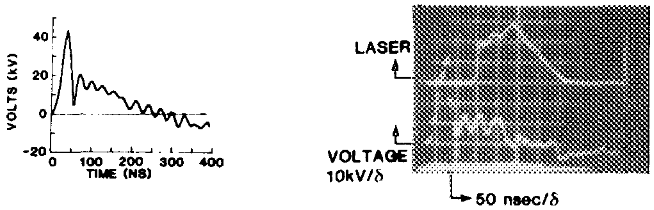
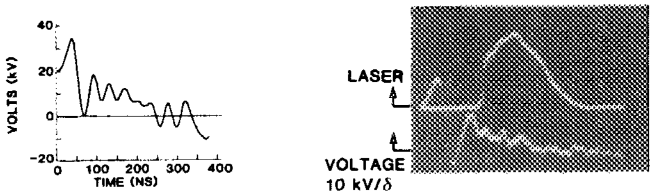
(a) RAIL GAP/SPIKER



(b) MAGNETIC DIODE/SPIKER



(c) MAGNETIC SWITCH/SPIKER

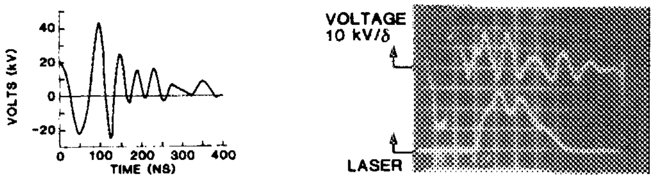


FIG. 2. Comparison of computer model predictions and experimental measurements of the voltage measured between the isolation switch and the laser head for the magnetic isolator and a rail-gap isolator. Also shown are photodiode traces of the laser pulse for these three cases.

PFL's and the dc charged spiker capacitor. The laser-head voltage was measured with a resistive divider connected between the ferrite isolator and the laser head. The discharge current was measured by electronically integrating the response of a *dI/dt* probe placed between the current return and the Lucite pressure vessel. The laser temporal pulse was measured with a vacuum photodiode looking at light transmitted through the maximum reflector indicating that the optical pulse duration was ≈ 150 ns.

Optimum laser performance was obtained with a gas mixture consisting of 5 atm Ne + 0.5% Xe + 0.03% HCl. Mixtures richer in HCl and Xe gave shorter pulse durations and lower efficiencies, presumably because of the onset of discharge instabilities.

In these experiments, the PFL was pulse charged in ≈ 11 μs from a dc charged storage capacitor. Because the laser head was directly connected to the PFL, the gas held off the PFL charging voltage, which was approximately twice the discharge self-sustaining voltage. Note that the magnetic circuit used here is not a magnetic pulse compressor driven XeCl laser as has been described earlier.[4] The bulk of the electrical energy is slowly charged onto the PFL connected directly to the laser head and then rapidly switched by the magnetically isolated spiker circuit. Once the x-ray gun was fired, the laser gas would avalanche in ≈ 200 ns for a PFL charging voltage of ≈ 20 kV. Thus timing between x-ray source and spiker was critical. With the spiker off, the laser was x-ray switched in analogy to de Witte's work.[2] The laser performance for this x-ray switched case was poor ($\sim 1.3\%$ efficiency), with no effort made to optimize it.

The magnetic isolator can be used in two distinct modes; either as a magnetic diode with the spiker and main PFL polarity the same, or as a magnetic switch with the spiker polarity opposite to the main PFL polarity. In the diode mode, the magnetic material is set to have low impedance for current flow from the main PFL to the laser head. The spiker pulse resets the magnetic material until the gas breaks down. The magnetic diode then opposes current flow from the main PFL until the inductor again saturates in the forward direction, allowing current flow from the main PFL.

In the magnetic switch mode, the spiker and main PFL polarity are opposite so that there is a current reversal between the spiker pulse and the sustainer pulse. The magnetic material is initially set by the pulse charging current to oppose current flow from the main PFL. The spiker pulse then saturates the magnetic switch allowing current flow from the main PFL. This minimizes the delay between the spiker and the main PFL pulse; but because the PFL is charged with opposite polarity from the spiker, the magnetic switch must have larger voltage hold off (core area) than for the first case in which the spiker and main PFL have the same polarity.

Both techniques were tried in these experiments and gave good performance. Oscilloscope traces showing the temporal waveforms for the voltage at the saturable inductor and the optical pulse are shown in Fig. 2(b) for the magnetic diode mode, and Fig. 2(c) for the magnetic switch mode and compared with the corresponding waveforms obtained with a rail switch isolator in Fig. 2(a).

In the magnetic diode mode shown in Fig. 2(b), the delay between the voltage collapse due to avalanche of the head and the main current rise is caused by the time required to resaturate the magnetic switch to allow current flow from the main PFL. The best performance was obtained by ad-

TABLE I. STI XeCl laser performance with spiker/sustainer circuits.

Isolator	PFL energy	Spiker energy	Laser energy	Efficiency[a] Expt.	Model
Rail gap	58.4 J (20.1 kV)	7.5 J (50 kV)	2.6 J	4.0%[b]	3.8%
Magnetic diode	58.2 J (19.8 kV)	12.5 J (50 kV)	2.6 J	3.6%[c]	3.6%
Magnetic switch	56.6 J (19.7 kV)	10.8 J (60 kV)	2.7 J	4.0%[d]	3.9%

[a] Efficiency = optical energy/energy stored on spiker and PFL.

[b] Energy for rail switch trigger not included.

[c] Efficiency with respect to dc charged primary capacitors = 3.6%.

[d] Efficiency with respect to dc charged primary capacitors = 3.9%.

justing the x-ray source and spiker timing so that the spiker voltage time product and, hence, this delay were minimized while still providing rapid gas breakdown.

For the magnetic switch mode case shown in Fig. 2(c), the voltage collapse is caused by saturation of the magnetic switch implying that the saturable inductor core area is too small. The gas avalanche is then completed by the main PFL voltage, which is too low to minimize the delay between voltage collapse and the onset of lasing. The results reported here were obtained with magnetic materials that were already on hand, which did not allow optimization of performance with respect to amount or configuration of the magnetic material. Optimization of the magnetic switch and the spiker circuit would undoubtedly lead to a further increase in efficiency.

A computer model was developed to describe discharge excited XeCl lasers and has been used to analyze our laser. The program includes all of the pertinent heavy particle and electron collision processes, a laser extraction model, and a component model of the electric discharge circuitry. Calculated voltage waveforms for the rail gap, the magnetic diode, and the magnetic switch configurations are plotted in Fig. 2 and compared with the experimental waveforms. The best performance for each of these configurations is summarized in Table I and compared with the best performance obtained with a rail-gap switch. The corresponding laser efficiencies calculated by the computer model are listed in Table I and agree well with the experimentally measured values. The magnetic switch mode yielded 4% efficiency at 2.7 J, equaling the best performance obtained with the rail switch. The volumetric energy density was 3.3 J/l. These experiments demonstrate efficient XeCl laser excitation with a spiker/sustainer circuit using a simple and reliable magnetic isolation technique that is scalable to high average powers and is generally applicable to other discharge lasers.

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