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LASER-TRIGGERED SWITCH MODIFICATION TO VEBA*

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Summary

The VEBA high current, relativistic electron accelerator has been modified for free electron laser experiments by replacing a self-closing water output switch with a laser-triggered gas switch. Reliable switch operation has been achieved in single and two channel discharges with output waveforms closely matching computer simulation.

Free Electron Laser

A collective free electron laser involves a three-wave interaction between a beam space charge mode, an incident wave (from a periodic magnetic field), and an exponentially growing backscattered wave. The combined periodic magnetic and backscattered fields cause a parametric instability which acts to bunch the electrons and increase the backscattering. For maximum efficiency the electron beam should be monoenergetic and the pulsed magnetic field must overlap the electron beam temporally. The latter condition can be met by command triggering both the electron beam and the magnetic field with sufficient precision. The former condition can be approached by increasing the efficiency of the energy transfer from the storage device to the transducer, and by precisely controlling the voltage at which the storage device is triggered.

Switch Requirements

Because of the short duration of the events involved, a switch reproducibility (jitter) of less than ±5 nsec is required. At the elevated voltages ($\sim 10^6$) and high energies typical, this constraint can become quite compelling. The efficiency of the coupling of the energy storage to transducer can be improved by decreasing the switch inductance. Such reduction reduces the rise-time of the pulse and decreases the energy losses associated with switching. While the overvolted water switch on VEBA had the advantage of very short risetime, the ripple on the output voltage generated a spread in electron energy which was too great to permit the required interaction between beam and field necessary to produce substantial laser output. A laser-triggered water switch would have preserved this short risetime, but was ruled out because the acoustic shock carried by the water in the switch region would have made the survival of optical components very difficult.[1] The voltage waveform predicted by the TEMP[2] computer code for a single channel, laser-triggered, gas dielectric switch shows acceptable ripple; however, the relatively slow rise-time drove the design to multiple channel switching in order to reduce switch inductance.

The TEMP code was used to predict expected voltage waveforms for single, dual, and triple laser-triggered switch (LTS) closures as well as a predicted form for the case of zero switch inductance. As expected, a dramatic decrease in risetime (> 30%) was predicted in going from one channel to two with a smaller gain in going to three channels. The zero inductance case was not too different from the three-channel prediction. Thus, the LTS was designed to accomodate up to three simultaneous channels to test the predicted limit on risetime and to better assure that at least two channels would be initiated each time.

Unlike the axial switching schemes of most previous work[3], the configuration of VEBA necessitated a radial introduction of the laser beam as shown in Fig.1. The beam splitting and focusing optics were located

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in the inner electrode so as to focus the laser beam along multiple paths onto the intermediate electrode. Timing was accomplished by initiating the slowest event (laser amplifier flashlamp) which in turn initiated the Marx gaps. A di/dt loop senses the Marx erection and the suitably delayed signal triggers the optical shutter (Pockels cell) of the laser.

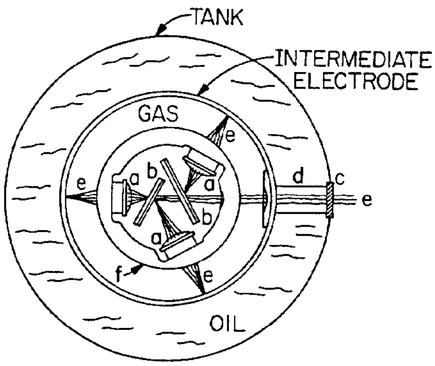

Figure 1
Radial Introduction of Laser Beam
a. lens c. window
b. beam splitter d. nylon tube
e. laser beam showing focussing
f. inner electrode

LTS Design

An LTS, in its simplest form, consists of a laser pulse introduced into the inner electrode region of a spark gap. Maximum efficiency results when the laser pulse is focused slightly into the anode The ionization produced in the dielectric gas leads to rapid, reproducible breakdown. For the free-electron laser work it is necessary to fire the laser onto the cathode; thus optimum conditions are not met.

With the basic design completed the details to be specified included: electrode material and configuration, optics mounts, type of dielectric gas, and laser output requirements.

The electrodes must be easily machinable, resistant to spark erosion, and must produce copious ionization when intercepting the focused laser beam. Previous work[4] has shown that stainless steel is a good choice. Because the breakdown arc is initiated at the focus of the laser beam, it is possible to increase erosion resistance and ionization production by installing flush mounted tungsten buttons in the host stainless steel electrode. Future plans call for this retrofit. The electrode configuration consisted of a ring affixed to the intermediate cylinder as the target and Rogowski-like contours on the inner cylinder drilled to allow laser egress.

The laser beam is turned into the switching region through a nylon tube which forms the interface between gas and oil dielectrics. The beam is focused by 6" focal length lenses onto the intermediate electrode. A single lens provides for single-channel operation while the addition of a 50% reflecting mirror and second lens produces two switch channels. A 33% mirror and a third lens will complete the three channel arrangement.

The dielectric gas was a 50:40:10 mixture of N_2, Ar, and SF_6. The switching delay varies inversely with the product of the Townsend ionization coefficient, α, and electron drift velocity, v.[5] Thus argon is used ($\alpha v \approx 150\ sec^{-1}$) even though it has a relatively small dielectric strength. Nitrogen ($\alpha v \approx 40\ sec^{-1}$) and SF_6 ($\alpha v \approx 5\ sec^{-1}$) give the required dielectric strength. It is possible, of course, to use a pure SF_6 dielectric[6], but a large increase in laser power is needed to offset the electronegativity of SF_6.

Based on previous work[7], it was estimated that a minimum laser power of 100 MW per channel would be required to reliably trigger the 8.9 cm gap at maximum voltage. The laser power required varies inversely with the reduced field, E/p, in the gap. Thus, much more laser power is required to switch 0.75 MV at 108 psi dielectric pressure (E/p = V/cm-torr) than to switch 0.5 MV at 40 psi dielectric pressure (E/p = 27 V/cm-torr). These two nominal operating conditions give 1.27 and 0.85 MV output voltages respectively due to transformer action.

Results

Preliminary

To determine the laser power requirements for full-up operation, the tiggering reliability for a single channel versus E/p and laser power was studied. At 130 psi reliable triggering was obtained for E/p down to 10 V/cm-torr with laser power of ≈70 MW. The LTS would still operate for E/p = 9.75 V/cm-torr but the jitter was very high. At 10.1 V/cm-torr the LTS failed to operate with a laser power of 35 MW.

Single Channel

For a 0.7 MV output the self-breakdown of the spark gap is 0.51 MV. The gap conditions are: 41.5 psia, 8.9 cm spacing, and 800 nsec risetime on the Marx voltage. The reduced field at self-breakdown is 26.7 V/cm-torr. A laser power of 30 MW was used for these studies. The laser pulse can be inserted any time during the 800 nsec voltage rise. Table 1 shows the delay and jitter of the LTS versus the time of laser insertion. Note that at the lowest insertion time (430 nsec) the reduced field in the gap is only 14.5 V/cm-torr.

TABLE 1

Insertion Time	Output Voltage	Delay	Jitter
700 nsec	0.66 MV	84 nsec	5.5 nsec
600	0.63	93	2.1
500	0.60	124	20.7
430	0.57	193	45.4

The pressure was increased to 108 psia on the 8.9 cm gap which resulted in self-breakdown voltage of 0.7 MV or an output voltage of 1.2 MV. The gap could not be reliably triggered with the 30 MW laser pulse due to the low value of E/p (≃ 12.8 V/cm-torr at 90% of the self-breakdown voltage.) Laser power was then increased to 70 MW (2.4 joules in 35 nsec) and a limited range of insertion times were used to produce the results in Table 2.

TABLE 2

Insertion Time	Output Voltage	Delay	Jitter
975 nsec	1.1 MV	83 nsec	6.5 nsec
920	1.01	88	9.1
875	1.07	96.5	7.9

The jitter here is worse than in the low-voltage, low-laser power case. This indicates that a minimum laser power of perhaps 150 MW per channel would be a more realistic design parameter.

Dual Channel

The beam splitter and additional lens were installed for two-channel operation. Laser power was kept at 120 MW nominal, thus a lower switch voltage (higher E/p) was used to increase the reliability of the switching. Previous dual channel switching[8] revealed that the two channels would share the current and thus reduce the risetime if the synchronization between channels was better than about half the output risetime. The predicted two-channel risetime is 20 nsec which means that the jitter must be better than ±10 nsec to achieve two-channel operation. Because jitter of less than ±10 nsec was achieved at E/p~20-25 V/cm-torr with a laser power of 30 MW, the prospects for dual channel switching with 60 MW per channel seemed very good.

Figure 2 is a digitized reproduction of a single channel and dual channel switching event. The risetime (10-90%) of the single-channel is about 40 nsec while that of the dual channel is 20 nsec. Very reliable dual channel switching was produced. In addition, the dual channel LTS produced a flat waveform with less than ±5% ripple for 4 nsec duration.

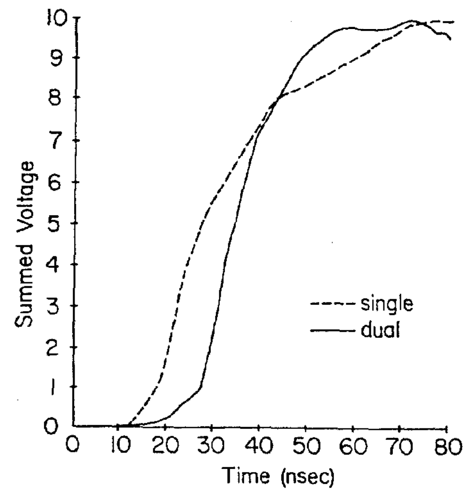

Figure 2
Digitized Traces of Single vs. Dual Channel Voltage Rise.

Conclusions

Laser-triggered switching has been used to initiate multiple channels in a gas insulated, pulse-charged spark gap. Future plans call for increased laser power to produce three channel switching at the elevated voltages needed for the FEL.

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