High Power Switch Design for the Nova Upgrade Laser

(Project Hercules)

FINAL Report

Period from 08-15-91 to 05-31-93

Subcontract: B157380

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High Energy Research Concerning the Ultimate Lifetime of Experimental Switches

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Introduction:

One promising approach to achieve nuclear fusion is to rapidly heat a sphere consisting of frozen hydrogen isotopes using a high powered laser. Pulsed lasers of this type are optically pumped using gas filled flashlamps. The light is generated, when a gas discharge takes place inside the flashlamp. The currents required for the needed optical output power are in the order of hundreds of kA's. The energy for the discharge is stored in capacitor banks which have to be switched into the flashlamps. Proposed closing switches needed for this application are new high power ignitrons. In the latter part of the 1980's, these new high power ignitrons have been developed mainly by Richardson Electronics and English Electric Valve (EEV) [1,2]. They are supposedly suitable for high peak power switching (100's of kA) and large charge transfer (100's of C). This project was designed to test the lifetime of these switches under a certain level of high power switching conditions.

Abstract:

A test facility has been constructed to test high power ignitrons using an electrolytic bank. The goal of this project, which was named Hercules (High Energy Research Concerning the Ultimate Lifetime of Experimental Switches), was to test the lifetime and switching characteristics of high power ignitrons for Lawrence Livermore's laser upgrade program. The main tubes of interest that have been tested were the NL-9000A from Richardson Electronics, and the BK-1002 from English Electric Valve (EEV). Both tubes have stainless steel, cup style anodes. Both tubes were connected in series for the tests. Required test parameters were $I_{\text{peak}} = 300 \text{ kA}$, and $Q_{\text{transfer}} = 200 \text{ C}$. During the tests, the BK-1002 tube failed due to ignitor shorting. The average forward voltage drop across the EEV tube was almost twice than the drop across the NL-9000A. After the tube failure, the BK-1002 was replaced by a NL-1057 to continue testing of the NL-9000A.

Test Setup:

Capacitor banks:

The test setup consisted of 6 capacitor banks containing a total of 4212 electrolytic capacitors, rated at 1500 μF , 450 Vdc each. Figure 1 shows an outline of the overall arrangement of the test facility. The individual capacitors were arranged in sets of 13 capacitors in series. To control the voltage distribution among the capacitors in series connection, Metal Oxide Varistors (MOV's), were used. Figure 2 shows the arrangement of 13 individual capacitors with MOV's and bleed-off resistors. It turned out, that the use of MOV's is much cheaper than using zener diodes for the same purpose. It is of course also possible, to control the voltage distribution solely by parallel resistors. However, to be effective for voltage control, the resistor values would have to be so small that they would introduce too much leakage current. In the project, 6 capacitor banks were connected in parallel to yield a total capacitance of approximately 38 mF. Each of the 6 capacitor banks contained a total of 54 series connected capacitor sets (containing 13 capacitors each). This amounts to a total of 324 sets of series connected capacitor sets totaling the aforementioned 4212 capacitors. The absolute maximum bank voltage is 5000V. As shown in Figure 1, the 6 capacitor banks were grouped in a star configuration around a test stand, that contained 2 ignitrons in series. Before all 6 banks were built, a test set containing 13 capacitors in series was built and fired into a small size C ignitron. The discharge was critically damped using a resistor for these preliminary tests. The peak discharge current, that was demonstrated using this series combination of capacitors during the preliminary tests was 1 kA. Approximately the same current is pulled out of all banks with a discharge current of 300 kA today, since all banks contain a total of 324 capacitor sets. In addition to the preliminary experimental tests, computer simulations using the PSpice program have been performed to back up the design. The electrolytic capacitors were obtained from Lawrence Livermore National Lab., where they had been used in a power supply for plasma containment magnets. The philosophy behind the design used here, was to use relatively low voltage capacitors with a high total capacitance resulting in a bank voltage of a few kV. As a result, only a minor portion of the energy stored in the bank has to be dissipated in a load, which is preferable for lifetime testing. However, in order to test the holdoff voltage capability of the tubes, a separate hipot circuit was necessary, since the bank voltage alone was too low. To yield realistic testing results, the hipot circuit has to be backed by a small capacitor, that has to be at least large enough, to cause a noticeable full breakdown, should a pre breakdown occur in a tube.

Fig. 1 Project Hercules Floorplan and Conduit System

1/16", .5"x3" copper connection piece

MOV in parallel with resistor, soldered to solder lugs and bolted across each capacitor

Fig. 2 Capacitor Set Design

The use of a separate hipot circuit made it necessary to use 2 ignitrons in series, since otherwise the connection to the high power bank would have to have been switchable, which is not feasible at the current levels of interest. The hipot circuit output is connected to the middle of the 2 series ignitrons. However, the placement of 2 ignitrons in series is not a drawback, since data on 2 tubes can be obtained simultaneously; allowing a direct comparison.

During the design phase of the experiment, several alternatives to the use of electrolytic capacitors have been studied. One alternative involved the use of 11 kV, 50 kJ Maxwell capacitors and a huge pulse transformer made by Stangenes Industries. The transformer would have decreased the voltage and increased the current level and the charge transfer by a factor of 5 - 10.

Test Stand:

In order to cancel the magnetic forces on the ignitrons and on the plasma inside the ignitrons in particular, the test stand featured a coaxial current return. Figure 3 shows a detailed drawing showing the construction of the test stand. The top plate and the vertical bars are made out of copper, whereas aluminum is used for the bottom plate. The bottom plate is used as the ground reference for the experiment. The top plate as well as the vertical copper bars are connected to the positive HV terminal of the banks. A total of 6 vertical bars corresponding to 6 capacitor banks were used. Not shown are 4 horizontal reinforcement rings made out of steel to contain the magnetic forces acting on the vertical bars. The middle plate shown in Figure 3 is made out of wood. Its purpose is to support the weight of the upper tube. The connections going to the anode of each tube were made with flexible copper braids to avoid mechanical stress to the glass or ceramic feed-through. As mentioned before, the output of the hipot circuit was connected at the junction of the upper and lower ignitron for holdoff tests between shots. During those tests, the top plate was grounded using a high voltage relay and a series resistor (to prevent damage to the relay in case of any residual charge on the banks). The hipot system itself is explained in more detail in a later paragraph. The high current connection from the banks to the test stand was made using a pair of low inductance coax cables per bank resulting in a total of 12 cables. This means that for a peak current of 300 kA each bank provides 50 kA and each cable 25 kA. This proved to be a conservative load for the cables and worked well.

SCALE: 1" $\approx$ 6"

Fig. 3 Hercules Stand Design

Main power supply:

In order to charge the main banks, a 12 kV, 10 A power supply was used. To control the output voltage and the charge rate, the primary voltage going to the main transformer of the power supply is controlled by a 3-phase variac. The input voltage of the variac is 480V rms line-line. Figure 4 shows a schematic of the main power supply. The major parts of the power supply are:

- The main 3-phase transformer
- The 3-phase high voltage rectifier
- The main contactors
- The instrumentation and control circuitry

Initially it was planned to control the power supply by putting SCR's into the primary delta of the main transformer as shown in Figure 5. In this configuration, the SCR's would vary the input voltage in a phase control mode. It was found however, that the voltage can not be reduced all the way down to zero, since the SCR's have a maximum turn on delay angle of approximately 150° due to recovery constraints. Not being able to control the voltage all the way down to zero created serious problems when the capacitor bank was connected, since a discharged capacitor bank initially acts like a short circuit leading to overcurrent problems. Therefore the SCR control was abandoned and a variac was used to control the power supply. The 3-phase variac stack consists of a total of 9 variable autotransformers; 3 in parallel for each phase. Special transformers on the output assured proper load sharing. The rating of the variac stack is 90 A per phase. The autotransformers are adjusted by a geared single phase AC motor. The up and down commands for the motor are controlled by the central control computer via optically isolated relays. In contrast to the SCR control, the variac design worked very well. The output voltage is now easily controllable down to zero and in addition no objectionable current harmonics, that are typical for SCR phase controllers, were created.

The overall experiment is served by a total of two main power feeds. One is the 480V main feed to the power supply described above. The other is a 120V feed, that powers the rest of the experiment including the hipot circuit. Both feeder lines have main circuit breakers which can be locked by pad locks in the "off" position to insure safety while working on the experiment.

Fig.5 Internal Connections for SCR Phase Controlling of Main Power Supply for Project Hercules (initial design)

HiPot circuit:

A schematic of the hipot circuit is shown in Figure 6. It consists of two high voltage power packs that charge a pair of capacitors through isolation resistors. Also included are dump relays and dump resistors for each power pack. The two power packs are wired in such a way, that activation of one will put positive voltage on the output of the circuit, whereas activation of the other one will result in negative polarity. This assures, that each tube can be tested with positive forward voltage. In order to hipot the tubes, the power packs are activated sequentially. During the hipot tests, the anode of the upper ignitron, which is identical with the output of the main bank, is grounded. All high voltage relays are controlled via opto-isolators by the central computer.

Fig.6: Schematic of the Hipot Circuit

Protection circuitry for the main banks:

Figure 7 shows a diode stack that was mounted on the output of each bank to prevent the bank voltage from reversing. The diodes are disk type devices, that are pressure mounted using three isolating rods. A disk resistor is also part of the stack to absorb energy during bank reversal.

Fig. 7 Reversal Damping Diode Stack
Design for Project Hercules

Diagnostics:

A shielded cabin contained all the controls and diagnostics. Probes for the main bank voltage, the current through the ignitrons, the differential voltage across each tube and the hipot voltage were installed. The differential voltage across the tubes was measured using 2 Tektronix model 6015, 40 kV high voltage probes and a differential amplifier for each tube. The differential amplifier is shown in Figure 8. The experiment was controlled by a IBM PS 2 computer. The computer was controlling the variac of the main power supply and the hipot circuit. This was done using an IEEE 488 hardware interface with optically isolated solid state relay outputs. In addition, a digital oscilloscope made by Yokogawa was connected to IEEE 488 port of the computer [Ref. 3]. Figure 9 shows the arrangement of the control and diagnostic system. The PS 2 computer, the hardware interface, the Yokogawa digital storage oscilloscope and the digital multimeters for the charging voltage are located inside a shielded cabin. Outside the cabin are the high voltage relays of the hipot circuit and the relays for the variac control. The overall control of the project is done by the software running on the PS 2 computer. It is written in GWBASIC. A complete listing is shown in the appendix.

DIAGNOSTIC PLAN

Fig. 9: Setup of diagnostics and control

After each shot, the oscilloscope traces were scanned by the computer in order to determine the peak current level and the differential voltage drop across each tube at the instant of the current peak. This gave an indication of the resistive drop across the tube, since the inductive $L di/dt$ component is zero at the current peak. The measured values as well as the differential voltages across both tubes before the shot are stored on disk. The sum of the voltages before the shot yields the charging voltage of the bank which can be compared with a direct dc measurement. Figure 10 shows one of the obtained data files. In this figure IP is the peak current in kiloamps, V1/PK, V2/PK are the voltage drops across the upper(1) and lower(2) tube at peak current, and TIME PK is the time from current onset to current peak. Finally V_TUBE_1 and V_TUBE_2 are the voltages across the upper and lower tubes before the shot. The voltage distribution is determined by a resistive divider. The divider was made using resistors in the megaohm range. This just sets a starting condition for the voltages across the tubes and should not have any effect on the high power test results after the tubes trigger. The total of the two latter voltages is the charging voltage of the bank.

NL9000A BK1002								
DATE	TIME	SHOT	IP [kA]	V1/PK	V2/PK	TIME PK	V_TUBE_1	V_TUBE_2
04-14-1993	16:16:12	1	72.9	372.8	157.3	.00027	532.5	118
04-14-1993	16:24:16	2	72.9	390.5	157.3	.00028	585.8	98.3
04-14-1993	17:13:39	3	140	674.5	255.7	.00031	1029.5	196.7
04-14-1993	17:18:44	4	148.8	692.2	295	.00031	1065	216.3
04-15-1993	15:03:43	5	67.1	390.5	137.7	.00027	568	78.7
04-15-1993	15:23:04	6	64.2	390.5	39.3	.00025	568	39.3
04-15-1993	15:27:00	7	134.2	710	196.7	.00029	1065	118
04-15-1993	15:32:16	9	250.9	1136	432.7	.00029	1810.5	275.3
04-15-1993	15:40:12	10	250.9	1171.5	432.7	.0003	1810.5	314.7
04-15-1993	15:46:02	11	268.4	1207	432.7	.0003	1952.5	354

Figure 10: Peak data file showing measured values during tests.

Periodically (set to every 25 shots), the complete voltage and current traces were saved to disk. For further evaluation, the files containing the traces in ASCII format have been reformatted to conform to the standard used by the PSpice post processor PROBE. The traces were then read into the PROBE postprocessor and further evaluated. Note that only the professional version of PROBE accepts the generated file format.

Test Results:

Figure 11 shows the voltage and current traces for a NL-1057 and a NL-9000A tube. In order to further evaluate the data, the charge transfer has been calculated by integration of the absolute value of the (ringing) current waveform using PROBE. In addition, the instantaneous power input into each tube and the total deposited energy per shot was obtained as shown in Figure 12.

Initially tests were conducted with a Richardson NL-9000A tube at the bottom of the test stand, and a Richardson NL-1057 tube on top. The NL-1057 was used as a temporary place holder for the BK-1002 tube from EEV. Using the two first mentioned tubes, test shots at moderate power levels up to 100 kA were fired. The initial goal was to test, calibrate, and tune the hardware and software of the experiment. During the first commissioning phase, the banks were charged up to the maximum design voltage of 5000 V. Unfortunately, at this voltage level, all MOV's of one series connected row of capacitors turned on. This was probably triggered by the failure of one capacitor. The subsequent overvoltage of the remaining string of MOV's resulted in a major explosion, that took out some 100 capacitors. It is important to note, that the V-I characteristic of MOV's is very steep at the knee voltage ($I_{knee} \approx V^{23}$). This means that only a slight reduction in maximum voltage will probably prevent such a mishap. After replacing the capacitors and testing the system, it was discovered, that voltages around 3000 V were adequate to achieve the required peak current level of 300 kA. The bank was therefore never charged close to 5000 V again, and has made no more problems since. As an additional safety feature, a setpoint meter with separate warn and dump setpoints was installed. The "dump" output of the meter was wired to the dump control of the main banks.

After the BK-1002 tube arrived, it was mounted on top of the NL-9000A replacing the NL-1057. Using those tubes, high power testing at current levels of 300 kA and 200 C total charge transfer was conducted. A total of 34 shots have been recorded for the combination of the NL-9000A and the BK-1002 tubes. Twelve of these shots are high power shots with peak currents over 200 kA. Besides those recorded shots, some more shots have been fired including one with I_{peak} over 300 kA. These shots could not be recorded for various reasons like failure of the scope to trigger etc.

Voltage and Current Traces

Date/Time run: 05-20-1993 15:49:58

Temperature: 27.0

Fig. 11: Differential voltage across the ignitrons and discharge current

Dissipated power and charge transfer in tubes

Date/Time run: 05-20-1993 15:49:58

Temperature: 27.0

Fig. 12: Integral to obtain Charge transfer, power and energy deposit

After about 40 shots, the BK-1002 failed to trigger due to shorted ignitors. Both the ignitor in use, as well as the spare ignitor, were found to have a resistance below 1 Ohm. In contrast, the resistance of the used ignitor of the NL-9000A tube was 300 Ohms, and the resistance of the unused ignitor was found to be 400 Ohms. Both tubes passed the hipot test with no prefires at 11.5 kV which is close to the limit for the insulation of the test stand. It was tried to clear the ignitor of the BK-1002 tube. In order to achieve this, the ignitor was pulsed at about 20 Hz for several minutes using a 0.1 μ F capacitor in series with a spark gap. This pulse circuit was suggested by Toni Shulski, who is a senior engineer at Richardson Electronics. This procedure was however unsuccessful.

Evaluation of arc resistance data:

All peak voltage data obtained from the combination of the NL-9000A and the BK-1002 was evaluated to determine the arc resistance at peak current. Fig. 13 shows the resistive voltage drops measured at peak current ($di/dt=0$) versus the peak current. On one occasion the voltage distribution differs from the norm, meaning that the NL-9000A had a higher voltage drop. The average arc resistance was determined from this data by linear regression. An average forward resistance of 1.78 m Ω was found for the NL-9000A tube. For the EEV 3.34 m Ω was found. This is shown in Fig. 14.

Conclusions:

An experimental setup for the lifetime testing of high power ignitrons has been designed, build and successfully operated. The capacitor banks make use of electrolytic capacitors. The advantage of the electrolytic capacitors is that the energy can be stored at a low voltage, making a load resistor unnecessary. Instead, the ignitrons constitute the load for the circuit. Since they are connected in series, differences in the arc resistance determine the voltage distribution and make a direct comparison possible. The voltage drop across the BK-1002 tube was considerably higher than the voltage drop across the NL-9000A. Accordingly, the peak power and the dissipated energy per shot are also higher. This is most likely caused by a larger anode-cathode spacing inside the EEV tube. As a result, the BK-1002 tube failed first. Similar results are reported in Ref. [4]. However in this reference the tubes are not connected in series and the arc drop data is similar for both tubes.

Fig. 13: Resistive voltage drops measured at peak current ($di/dt=0$)

*each point is a point
some measurements
show to occur
at 100 to 350 kA*

Fig. 14: Average arc drop voltage at peak current ($di/dt=0$).

References:

- [1] R. Kihara, D.B. Cummings, K.S. Leighton and A. Shulski , "Commercial High Current Ignitron Development", Proceedings of the 7th Pulsed Power Conference, Monterey, California, June 12-14, 1989, p. 18...21.
- [2] D.L. Loree, M. Giesselmann, M. Kristiansen, A. Shulski, R. Kihara, "Recent Advances in High Power Ignitron Development", IEEE Transactions on Electron Devices, Vol 30, No. 4, p. 720..725, April 1991.
- [3] D. Loree, M. Giesselmann, M. Kristiansen, D.Larson, " Status Report on Project Hercules", Proceedings of the 6th Symposium on Electromagnetic Launch Technology, Austin, Texas April 28-30, 1992.
- [4] C.R. Spikings, C.M. Oxley and J.R. Beacham, "High Current Evaluation of the New Size E Ignitrons with a Ringing Waveform", Proceedings of the 8th IEEE Pulsed Power Conference, June 16-19, 1991, San Diego, CA, p. 495... 499.

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