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Recently there has risen a strong interest in producing negatively charged ion beams such as H^-, for space based accelerators. The negative ions are generated in the plasma of an arc or glow discharge. The electrons are separated from the negative ions by a magnetic field. In such an environment various plasma instabilities can occur resulting in undesirable Megahertz noise of broad spectrum in the beam. This report describes the design of a possible noise suppression circuit utilizing power transistors in a pulsed discharge. Using power transistors it is possible to obtain high dynamic impedance; but still with sufficiently low D.C. resistance to stabilize the instabilities. The noise is present within a Negative Ion Source obtained from Los Alamos National Laboratories (AT division). This report describes the design of a Gate Turnoff Thyristor (GTO) pulsing circuit for the Negative Ion Source which includes the modification of an existing gate drive unit for a low power Gate Turnoff Thyristor.

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Final Report
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B. Cheo

D. Bruno

July 1, 1992

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ABSTRACT

Recently there has risen a strong interest in producing negatively charged ion beams such as H^-, for space based accelerators. The negative ions are generated in the plasma of an arc or glow discharge. The electrons are separated from the negative ions by a magnetic field. In such an environment various plasma and discharge instabilities can occur resulting in undesirable Megahertz noise of broad spectrum in the beam. It has been experimentally shown that the noise could be reduced by using a large ballast resistor in the discharge circuit. However to effectively suppress the noise, the value of the resistance would be prohibitively high.

This report describes the design of a possible noise suppression circuit utilizing power transistors in a pulsed discharge. Using power transistors it is possible to obtain high dynamic impedance; but still with sufficiently low D.C. resistance to stabilize the instabilities. The noise is present within a Negative Ion Source obtained from Los Alamos National Laboratory (AT division).

This report describes the design of a Gate Turn Off Thyristor (GTO) pulsing circuit for the Negative Ion Source which includes the modification of an existing gate drive unit for a low power GTO. The Negative Ion Source had been pulsed by a capacitive bank discharge circuit. This GTO pulsing circuit has been successfully tested on a Hollow Cathode discharge.

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Introduction

A) Negative Ion Source [1]

Figures 1 - 3 describe the negative ion source obtained from Los Alamos National Laboratory.

Figure 1 entitled Small Angle Source shows the approximate size of the source and the important components. An arc discharge occurs between the cathode and the anode. The cathode is tubular in shape then rises up into a "U" opening at the top so that the anode may slide into it. An insulator separates the cathode from the anode. Permanent magnets sit to the sides of arc region. The magnetic field is 2.4kG in the arc region. The purpose of this magnetic field is to trap the electrons. The H^- ion has a larger mass therefore its radius of revolution is much larger around the magnetic field than the electron which allows the H^- ion to escape through the slit at the top of the source.

In addition to the magnetic field there is an extraction unit (which was not used for this experiment) which pulls the H^- out of the discharge volume by the application of an electric field. The extractor is approximately rated at 100 kilovolts and 500 milliamperes.

Figure 2 is a simpler drawing of the discharge volume. The volume is 12mm in length, 4.3mm in depth, and 3mm in width. the direction of the magnetic field is also

SMALL ANGLE SOURCE

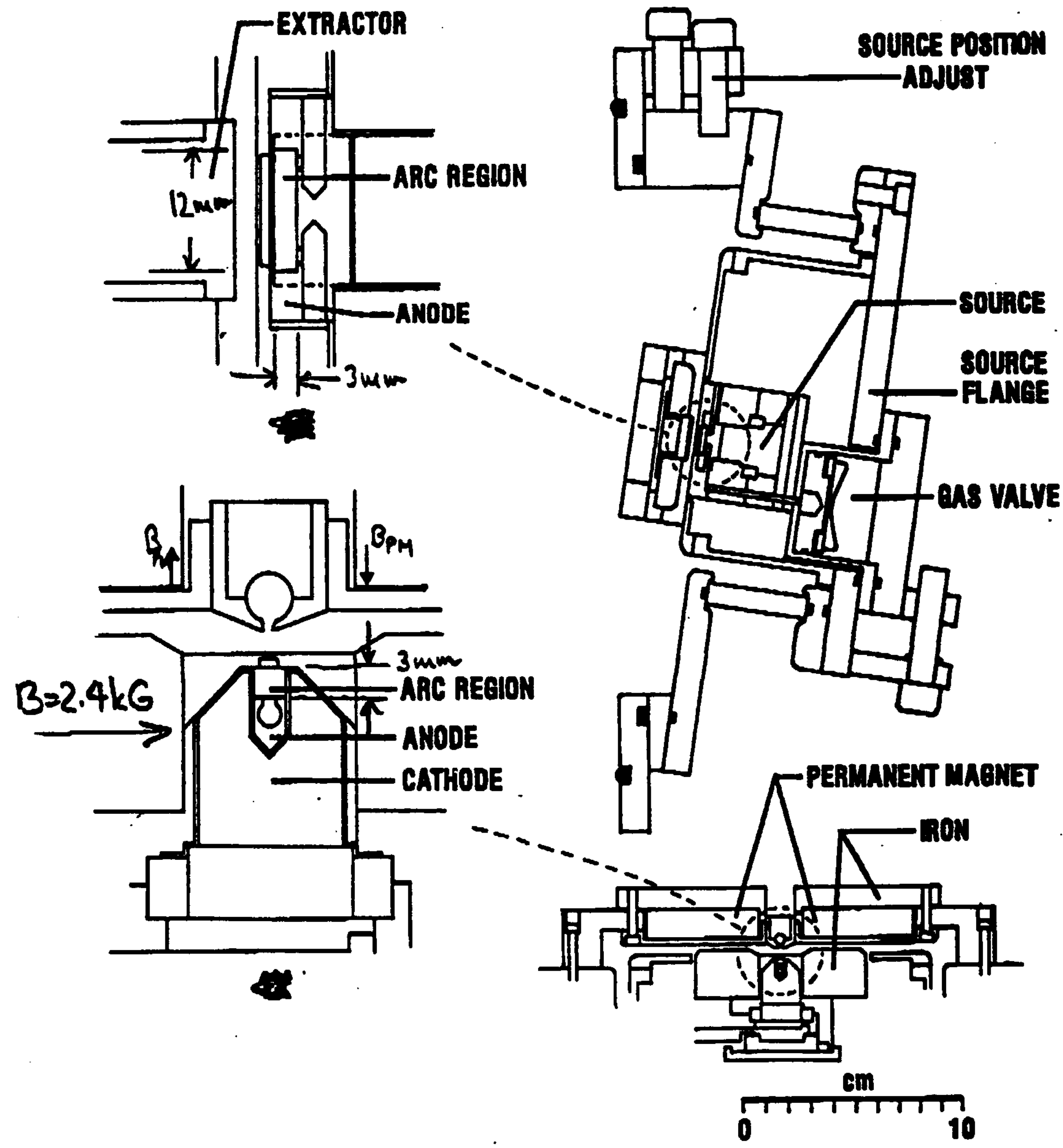


Figure 1

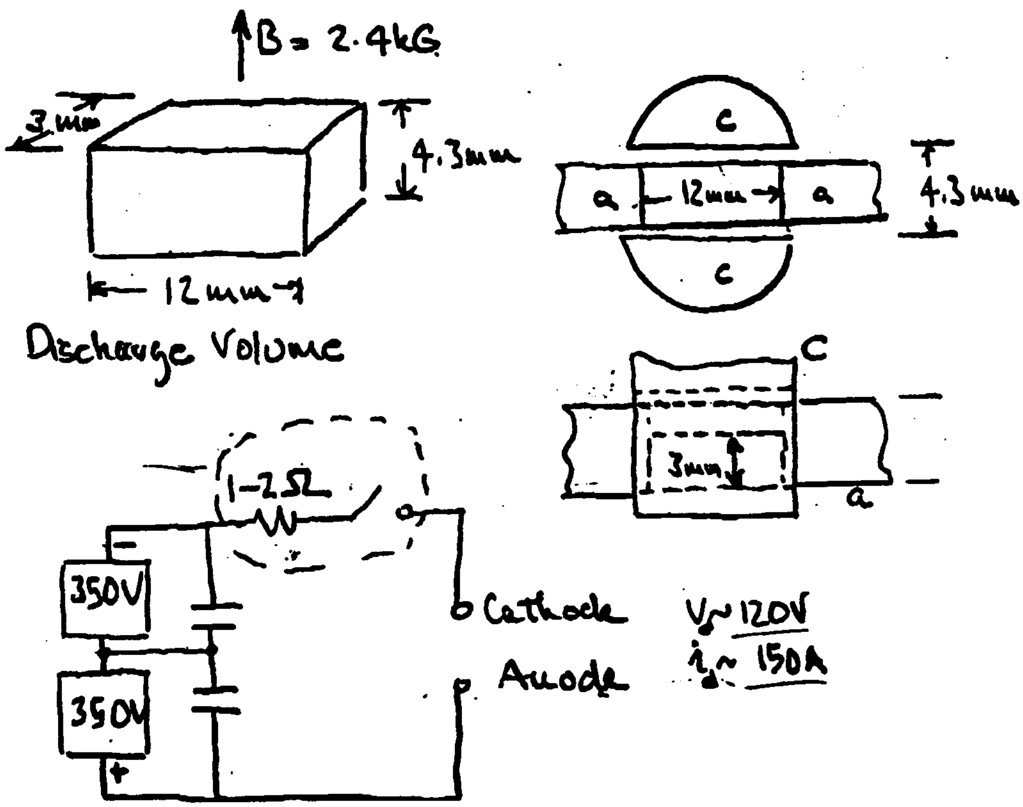

B = 2.4kG
3 mm
4.3mm
12 mm
Discharge Volume
c
a
12mm
a
4.3mm
c
C
3mm
a
1-2Ω
350V
350V
Cathode
Anode
V ~ 120V
i ~ 150A

Figure 2

indicated. A top view of the volume shows how the anode sits in the cathode "U" shape. The insulator is not shown between the anode and the cathode. Again the 12mm is shown and the 4.3mm is shown. The side view shows the 3mm height of the discharge volume in comparison to the cathode and the anode.

Figure 2 also contains a rough sketch of the discharge circuit used by Los Alamos National Laboratory. Two 350 volt D.C. power supplies are used to charge a capacitor bank and then a transistor switch is used to discharge the capacitor bank through the Negative Ion Source. The period of the pulse is 1ms, the frequency is 5hz and the amplitude of the pulse is approximately 150 amperes at 120 volts. The average current turns out to be very low (0.5 amperes). The gas into the Negative Ion Source is also pulsed. The gas pulse width is 5ms and the frequency is also 5hz. The arc pulse and the gas pulse are synchronized so that the gas pulse occurs then 4ms into the gas pulse the arc pulse occurs. This way the gas can be sure to fill the volume of the source (first 4ms of gas pulse) then during the last 1ms of the gas pulse the arc pulse (1ms) occurs. The arc pulse occurs during the last 1ms of the gas pulse. The gas is pulsed so as to put less of a strain on the pumps since the source requires the gas in it for only the amount of time the arc pulse is present. A figure will be shown later to illustrate the two pulses and more detail will be given about the gas pulse circuit.

Figure 3 contains the Negative Ion Source parameters. The operating voltage and the operating current are shown. The magnetic field of 2.4kG is also shown. The source

n_{H_2}	$4\times10^{15}/cm^3$	H_2 density without discharge
n_e	$3\times10^{14}/cm^3$	Electron density determined by spectroscopy
T_e	0.5eV	Determined by optical spectroscopy
V_d	120-80V	Operating discharge voltage
i_d	150A	Operating discharge current
j_d	$208A/cm^2$	Discharge current density at each cathode, $i_d/2wl$
w	3mm	Anode slot width along Z
l	12mm	Anode slot length along Y
L	4.3mm	Cathode-cathode gap along X
B_x	2.4kG	Source magnetic field, uniformity a few %
g	2.5mm	25-kV extractor gap
Q_{H_2}	100sccm	Operating instantaneous gas flow
$\bar{Q}$	5sccm	Average gas flow for 5-Hz, 10-ms gas pulses
T_c	200-300°C	Monitored cathode temperature
T_a	200-250°C	Monitored anode temperature
j_-	$2.9/cm^2$	Extracted H^- current density
i_-	160mA	Measured beam current from 7- by 0.8-mm slit at 25kV extraction
ϵ	0.017- by 0.006πcm-mrad	rms or 39.6% emittance values at 25 kV measured on ion-source test stand, best result. Can easily be 10-20% higher

Assumed or calculated values for other quantities

γ	5.5	Secondary electron emission coefficient, j_e/j_+ at cathode
K	0.7	Secondary negative ion emission coefficient, j_-/j_+ at cathode
n_H	$4\times10^{14}/cm^3$	Wild guess for H atom density, 10% of H_2 density
j_+	$29A/cm^2$	Positive ion current density at each cathode, $j_d/(1+K+\gamma)$
j_-	$20A/cm^2$	Negative ion current sputtered from each cathode, $Kj_d/(1+K+\gamma)$, 100V ions
λ_D	$3\times10^{-5}cm$	Debye length

Figure 3

of the magnetic field are two permanent magnets made of sintered cobalt. These magnets are actually man made. The sintering process enhances the magnetic field but also makes it very difficult to machine. The material cracks very easily (uneven as well) but is not easily cut.

Figure 4 is a look at the source as it sits on a large circular copper block for cooling purposes. Copper tubing runs around the copper block with either Freon or water going through it. For this experiment water ran through the tubing, however, Los Alamos uses Freon. This figure also shows the placement of the pulsed gas valve, the cathode thermocouples feedthroughs and the arc leads feedthroughs. These are all shown from the bottom of the source. When the source is turned to the side (also in figure 4) one can see a rectangular block protruding out of the baseplate. This is where the anode housing would be placed.

The gas valve is a Piezoelectric valve. By the application of an electric field on a crystal mechanical stress is placed on the crystal causing it to open and close. Figure 5 is a cross sectional view of the valve which is made by VEECO.

Feedthroughs are provided for connections to the source and for monitoring purposes so as to maintain the integrity of the vacuum. The gas flow for the source is 5-6 sccm (standard cubic centimeters).

The cathode thermocouples monitor the temperature of the cathode as it heats up. Two 150 watt heaters are embedded in the anode housing to heat the cathode before

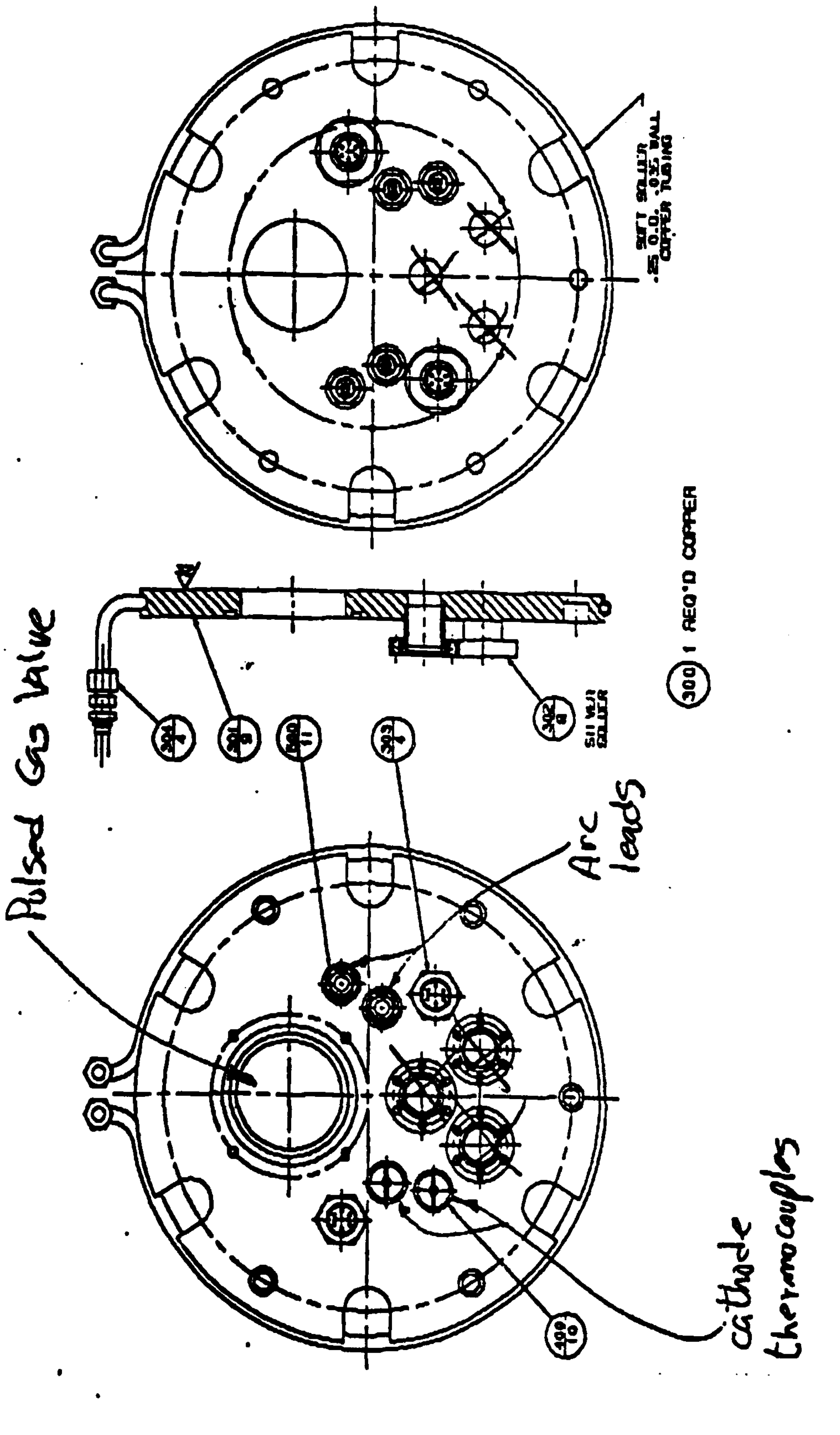
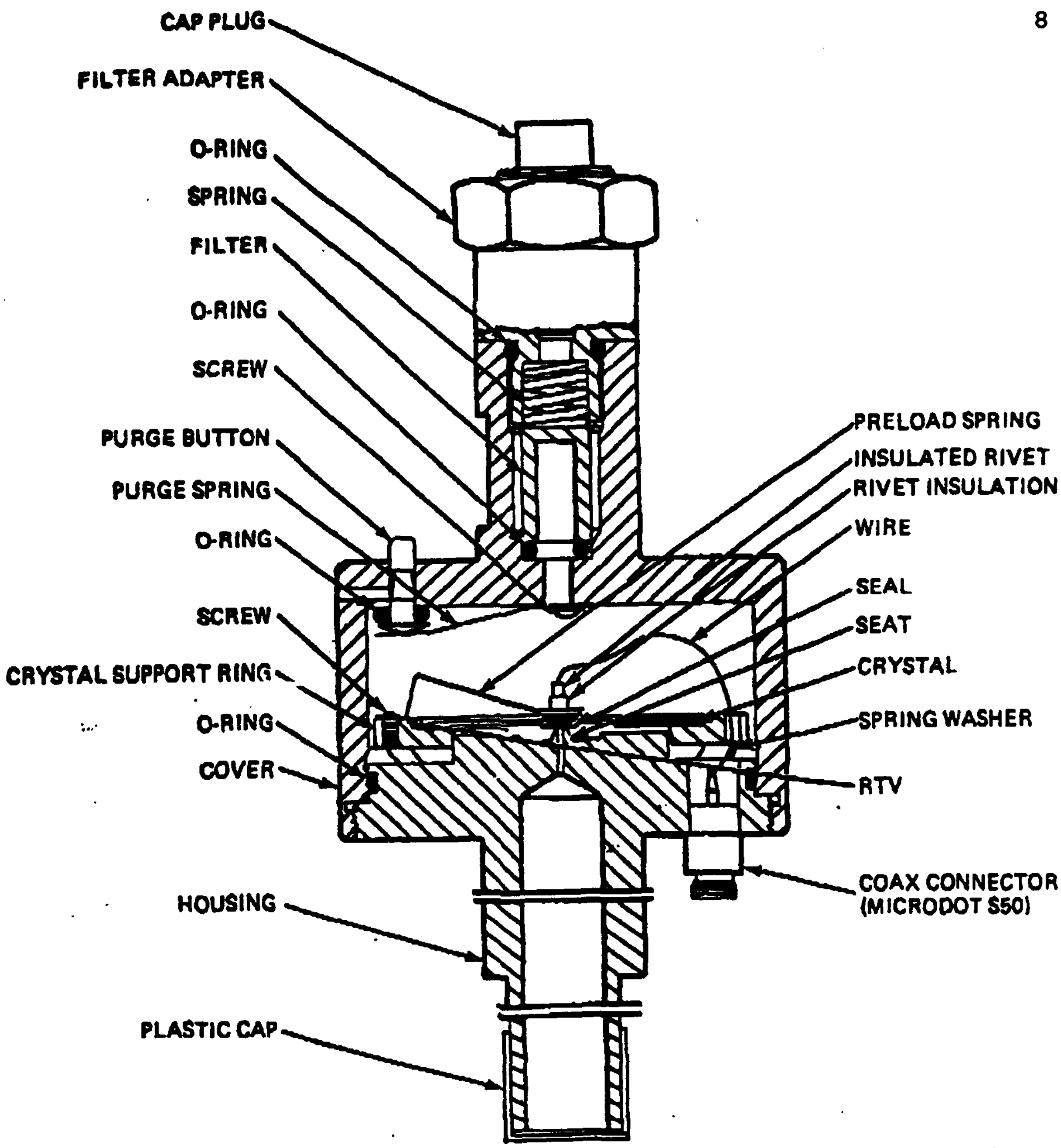

Pulsed Gas Valve
Arc leads
cathode thermocouples
1 REQ'D COPPER
SOFT SOLDER .25 O.D. .035 WALL COPPER TUBING
SILVER SOLDER

Figure 4



PV-10 VALVE CROSS SECTIONAL DIAGRAM

Figure 5

the arc pulse is applied. Feedthroughs are also provided for the heaters but are not labelled in Figure 4. The heating of the cathode can be called a sort of "priming" of the discharge or a "preionization" [9]. The cathode is coated with Cesium. Cesium contains one electron in its outer shell. If the Cesium (or the cathode) is heated to a high enough temperature this electron will "boil" off the Cesium and into the discharge volume. Now when the arc pulse is applied there will be a much larger percentage of free electrons in the gas then there would be if no Cesium had coated the cathode and been heated. The importance of this lies in the fact that the arc discharge will now be uniform where as without those extra free electrons on parts of the discharge volume may have had an arc initiated and not the whole volume. Initially there are very few free electrons in the Hydrogen gas and these come from cosmic radiation. One cannot depend on these few free electrons for a uniform discharge. That is why the cathode is coated with the Cesium and heated before the arc pulse is applied.

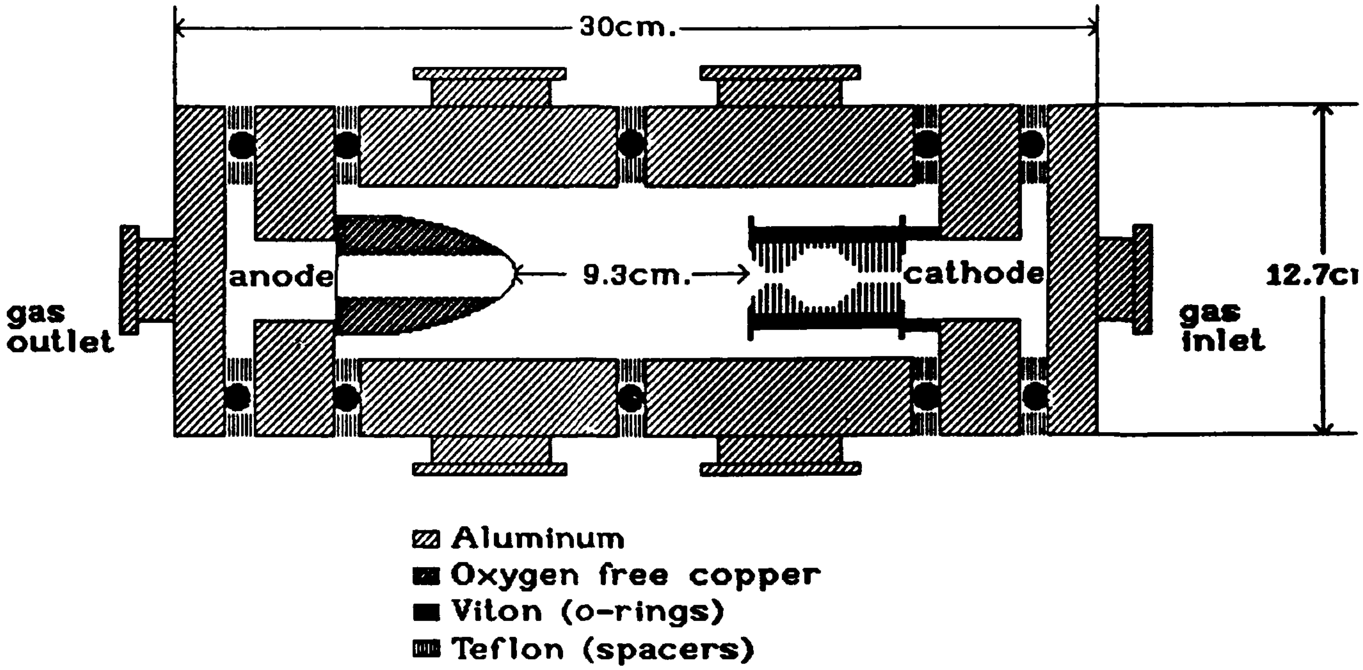
Once these free electrons are present the arc pulse is applied. The electrons are accelerated in the field towards the anode. Along the way to the anode some electrons collide with a neutral hydrogen atom. Some of these electrons knock off the outer electron of the Hydrogen atom. This Hydrogen atom is now a positive Hydrogen Ion or a proton which is now accelerated towards the cathode. Once this proton collides with the cathode more electrons may be released by secondary emission. Some electrons may not knock off the outer electron of the Hydrogen atom. Some electrons may bond to the

Hydrogen forming a Negative Hydrogen Ion [1]. The physics is not clearly understood but this is H^- ion that is most sought after.

B) The Hollow Cathode Discharge

The pulsing circuit was tested on a Hollow Cathode discharge [9]. Oscilloscope photos are shown later of the voltage and current pulses. A known operating discharge was needed for testing the pulsing the circuit and this discharge was present in the laboratory. Figure 6 is a cross sectional view and a photograph of the Hollow Cathode discharge electrode housing.

Both the anode and the cathode are placed in the electrode housing. The gas is fed in from the cathode end and pumped out the anode end. Six ports (flanges with windows) allow for diagnostics and viewing of the discharge. Viton o-rings maintain the vacuum. Teflon spacers ensure electrical isolation of each section of the electrode housing. The distance between the cathode and the anode is 9.3cm (3.65in). The material used for the electrode housing itself is Aluminum. During operation of the discharge the cathode may be viewed through the right front view port as well as the back view port and the right end view port (see Figure 6). The anode may be viewed through the left front view port as well as the back view port and the left end view port. Water cooling lines are at the top and bottom of the electrode housing. Each Aluminum plate that the electrodes are screwed to is also water cooled. The overall length of the


30cm.
anode
9.3cm.
cathode
12.7cı
gas outlet
gas inlet
Aluminum
Oxygen free copper
Viton (o-rings)
Teflon (spacers)

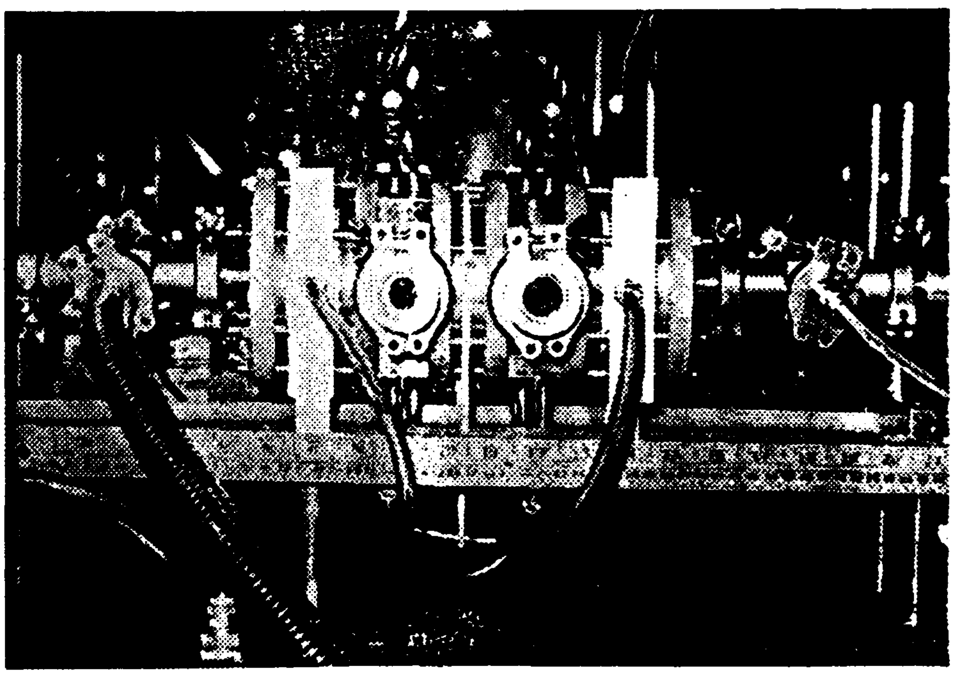


Figure 6

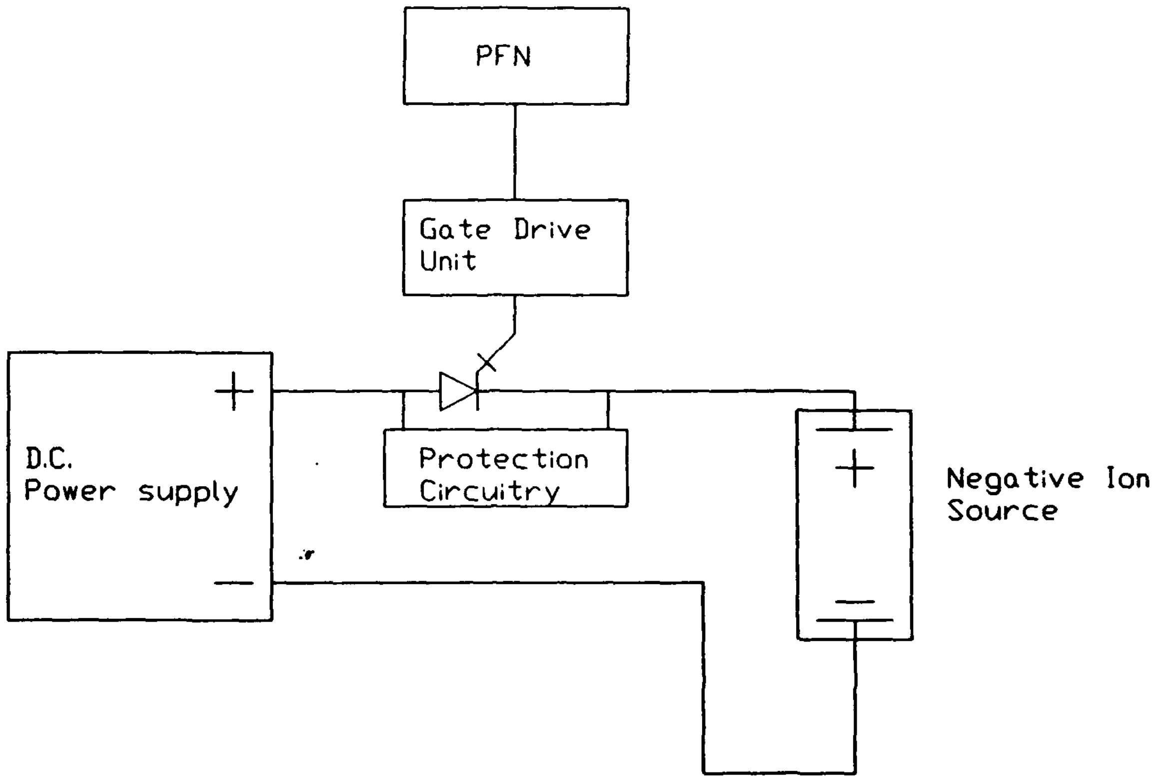
electrode housing is approximately 30 cm (about 12in). G-10 insulator rings, bolts and nuts keep the electrode housing and can be seen in the photo.

Negative Ion Source Pulsing Circuitry

A) The GTO and the Discharge Circuit

The GTO chosen to pulse the Negative Ion Source is sold by Marconi Circuit Technologies [8]. The model number is GT224K. The main reasons for using to using the GTO were twofold. One reason is that Los Alamos already experienced the noise in their source by using a capacitively discharged circuit, therefore by using the GTO we would show weather or not the noise was still present with a different pulsing technique. If the noise was not present, with the GTO pulsing the source, then the problem would be solved. If the noise was still present then it would further prove the source of the noise was in the Negative Ion Source rather than external to the source.

Another reason for using the GTO was the need for a high power electronic switch which could be implemented easily and quickly. Except for some protection circuitry the GTO is placed in series with the Negative Ion Source (see Figure 7)and the power supply (see Figure 8). The GTO has an anode, a cathode and a gate. Unlike an SCR (Silicon Controlled Rectifier) [2] the GTO requires not only pulse to turn it on but also a pulse to turn it off, hence the name "GATE TURNOFF THYRISTOR".



note: shown without noise suppression circuitry

Figure 7

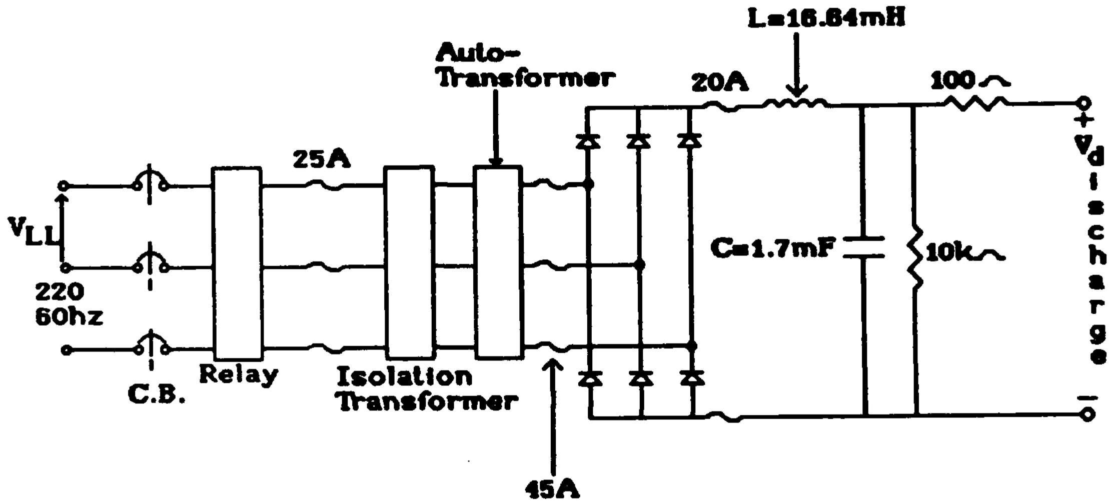

L=16.64mH
Auto-
Transformer
20A
100Ω
+
25A
V_LL
C=1.7mF
10kΩ
220
60hz
Relay
C.B.
Isolation
Transformer
45A
V_discharge
-

Figure 8

The gate drive unit [6] provides the amplified pulses and isolation for the GTO. The pulse enters the GTO between the gate cathode junction. The PFN (Pulse Forming Network) provides two pulses for the gate drive unit. The delay between the two pulses determines the on time of the GTO.

The advantages of using the GTO thyristor as opposed to conventional fast switching thyristors are [6]:

1. Simplified power circuit configuration.
2. Lower volume and weight.
3. Less Electrical and audible noise.
4. No commutation losses.
5. Greater power conversion efficiency.

Set against this it is necessary to have a more sophisticated gate firing circuit (gate drive unit) to perform the turn-on and more particularly turn-off function. For this project an existing gate drive unit was built and modified to turn off the higher current of 100 amperes. The main applications for GTO's are variable speed a.c. motor drive inverters, Choppers, Induction heating, Uninterruptable power supplies, welding, DC to DC converters, High voltage converters and Traction.

The GTO used here is the GT224k. The parameters of interest are:

1. Repetitive peak off-state voltage range...800volts-1200volts, this more than 3 times the normal operating voltage of the source

(3*120volts=360volts).

2. Repetitive peak controllable on-state current...300 amperes, this is twice as much as the operating current of the source.

Figures 9 and 10 are data sheets on the GT224k GTO. Figure 10 contains important information regarding the protection circuitry for the GTO. This protection circuitry is called a "snubber network" (see Figure 7 and Figure 11). A GTO can be destroyed if the dv/dt or di/dt is higher than it can withstand. The snubber network alleviates this problem. Assume the on pulse turns the GTO on. The GTO is represented by a closed switch in Figure 11. Now the main circuit current is flowing through the GTO. Next the off pulse comes to turn the GTO off. The GTO is now represented by an open switch in Figure 11. This is when the damage can occur. The current will try to go to zero instantaneously and the full power supply voltage will be across the GTO. The snubber circuit gives the current an alternate path. Since the current going through a capacitor changes instantaneously a capacitor is put in parallel with the GTO. Now when the GTO opens the current goes through the capacitor. A diode is also placed in series with the capacitor. A resistor is in parallel with this diode. When the current goes through the capacitor it will also go through the diode but not the resistor (ideally) since the resistance of the diode is much smaller than the resistor (26 ohms). Therefore the current can still go through the capacitor without seeing the 26 ohm resistor. The diode and resistor are needed for when the GTO turns on again. When the GTO closes the

Marconi
Electronic Devices

Gate Turn-Off Thyristor

GT224K Series

I_{TCM} = 300 A
V_{DRM} = 1200 V

Type Number	Repetitive Peak off-state Voltage NOTE: Gate/cathode resistor < 18 ohms V_{DRM}	Repetitive Peak reverse Voltage V_{RRM}
GT224K12	1200	16
GT224K10	1000	16
GT224K08	800	16

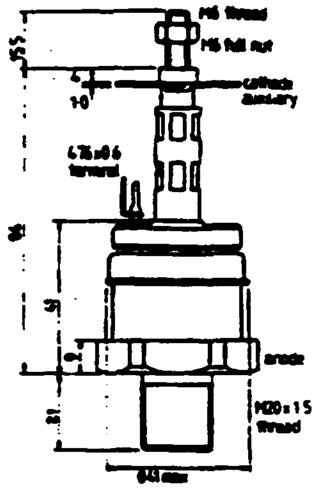
Outline K

For full detailed dimensions and notes refer to manufacturer

M6 thread
Min. torque 2.3Nm
Max. torque 3.4Nm
Weight (typical) 325g

Large nut
45.7 max across corners
41 across flats

All dimensions are in mm.



CURRENT RATINGS

I_{TCM}	Repetitive peak controllable on-state current		300 A
$I_{T(AV)}$	Mean on-state current	T_{HS} = 80 °C	100 A
$I_{T(RMS)}$	RMS on-state current	T_{HS} = 80 °C	150 A
$R_{th(j-hs)}$	D.C. thermal resistance junction to heatsink surface	Mounting Torque 30 Nm anode side	.2 °C/W

SURGE RATINGS

I_{TSM}	Surge (non-repetitive) on-state current	10ms half sine, T_j = 125 °C	1800 A
I^2t	I^2t for fusing	10ms half sine, T_j = 125 °C	16200 A^2s
dI/dt	Critical rate of rise of on-state current	From 600 V to 300 A T_{case} = 125 °C I_{FG} > 10 A, rise time < 1.0 us	500 A/us
dV/dt	Rate of rise of off-state voltage	R_{GK} 18 ohms, 50 % V_{DRM} T_{case} = 125 °C	500 V/us

GATE RATINGS

V_{RGM}	Peak reverse gate voltage	This value may be exceeded during turn-off	16 V

TEMPERATURE RATINGS

T_{vj}	Virtual junction temperature		125 °C

Figure 9

GT224K Series

I_{TCM} = 300 A
V_{DRM} = 1200 V

Marconi
Electronic Devices

CHARACTERISTICS - T_{case} 125 °C unless otherwise stated

			Limit	
			Typical	Maximum
V_{TM}	On-state voltage	At 300 A peak. $I_{G(ON)}$ =2.0 A		2.1 V
I_{DM}	Peak off-state current	R_{GK} < 18 ohms		25 mA
t_{gt}	Turn on time	I_{FG} = 10 A, rise time < 1.0 us From 750 V to 300 A, Resistive load		5 us
t_{gs}	Storage time	From 300 A to 750 V		10 us
t_{gf}	Fall time	Snubber 15 ohms, 1 uF. di_g/dt = - 15 A/us		1.3 us
t_{gq}	Gate controlled turn-off time	Resistive load		11 us
• V_{GT}	Gate trigger voltage	V_D = 24 V, I_T = 5 A. T_{case} 125 °C		.75 V
		T_{case} 25 °C		.9 V
		T_{case} -40 °C		1 V
• [illegible]	Gate trigger current	V_D = 24 V, I_T = 5 A. T_{case} 125 °C		.8 A
		T_{case} 25 °C		1 A
		T_{case} -40 °C		1.6 A
[illegible]	Reverse gate cathode current	V_{RGM} = 16 V. No gate/cathode resistor		25 mA

Figure 10

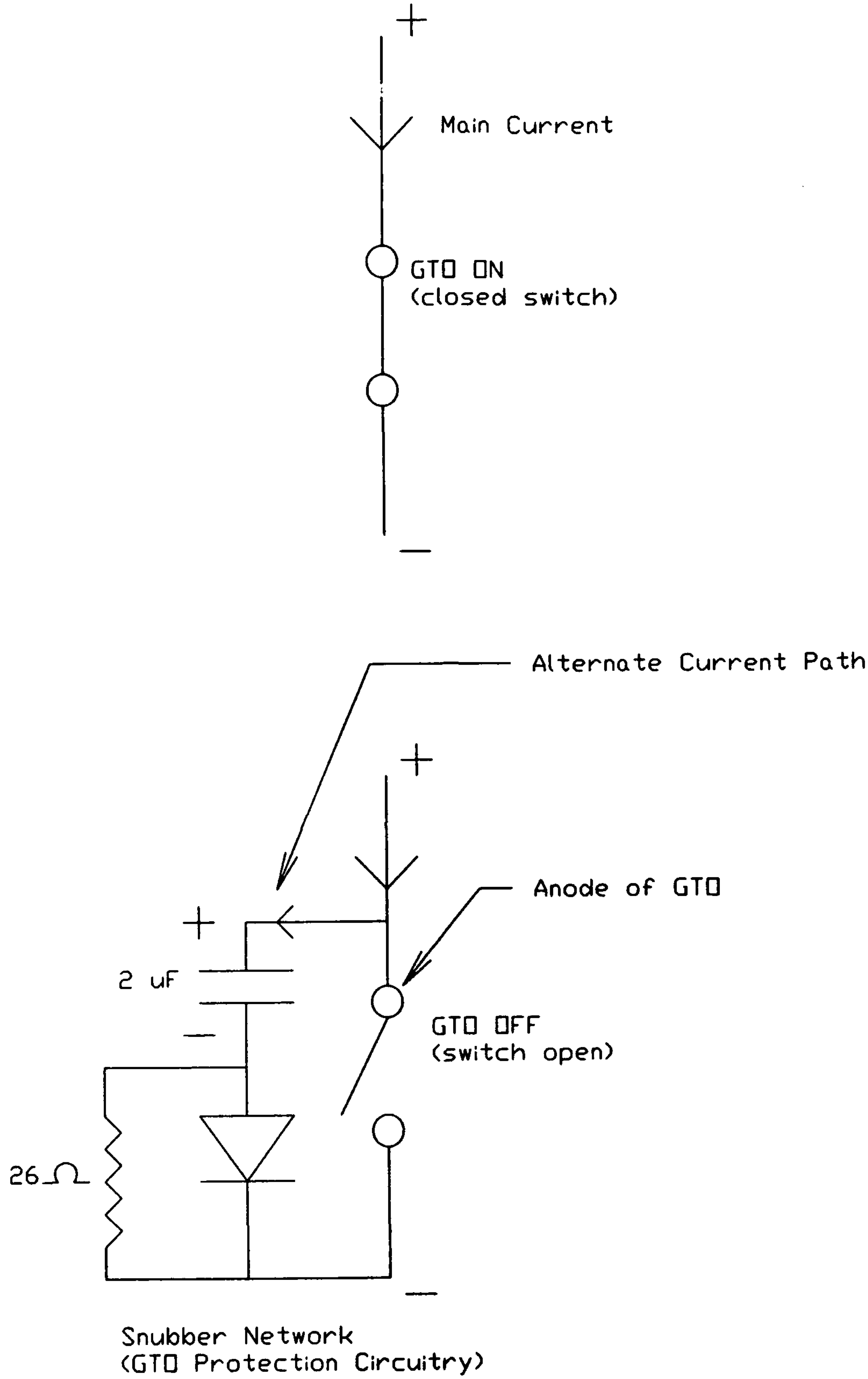

+
Main Current
GTO ON
(closed switch)
−
Alternate Current Path
+
Anode of GTO
+
2 uF
−
GTO OFF
(switch open)
26 Ω
−
Snubber Network
(GTO Protection Circuitry)

Figure 11

capacitor will be charged up to a certain voltage with the polarity positive at the top where the current entered and negative at the bottom where the current exited. The capacitor will now discharge through the closed GTO with the current leaving the top of the capacitor, entering the anode of the GTO, leaving the cathode of the GTO, and now will flow into the resistor in parallel with the diode and then back into the capacitor. It cannot get through the diode since it runs into the cathode. The purpose of this resistor is to slow down the discharge of the capacitor so as not to damage the GTO when the GTO turns on again. The purpose of the diode is to let the current flow through the capacitor instantaneously when the GTO opens up so as to reduce the high di/dt. The disadvantage to this is that the current in the main circuit does not turn off as fast because the capacitor cannot charge up instantly. Once it does, the current in the main circuit stops flowing.

Figure 10 lists the resistance as 15 ohms and the capacitor as 1 uF for the snubber circuit. After going through an RLC analysis [3] of the main circuit and the snubber circuit for when the GTO turns off, a capacitance of 2 uF and a resistance of 26 ohms were chosen. Figure 12 is a plot of the capacitor voltage versus time. Ideally the capacitor should charge up instantly, however the voltage could overshoot if it is too fast and damage the circuit instead. The overshoot would correspond to the underdamped case. With the values chosen the circuit would be either critically damped or closer to overdamped so as to avoid having the circuit going into oscillation as in the t := 0,0.000001 ..0.001

$$v(t) := 600 - 601.346 \cdot \exp\left[-1.903 \cdot 10^{4} \cdot t\right] + 1.346 \cdot \exp\left[-4.04 \cdot 10^{5} \cdot t\right]$$

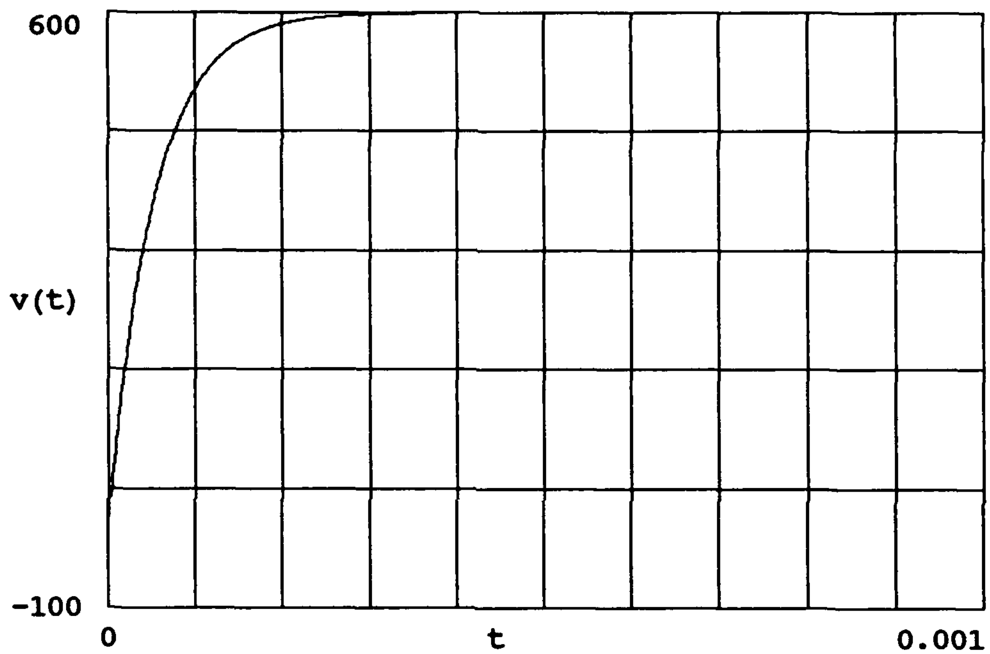


Figure 12

underdamped case.

Figure 13 contains general switching waveforms for the GTO [8]. The waveforms at the top are the anode voltage and current. The bottom two waveforms are the gate voltage and current. The GTO is driven on by a pulse of current and driven off by a pulse of current. It is very important to also understand that to turn off a GTO at least 1/3 of the on-state current must be supplied to the gate. This is why the existing gate drive unit for the low power GTO had to be modified. It could not turn off the high power GTO in this project. The current supplied to this GTO to turn it on is only about 2 amperes which is much less than the on-state current. For an on-state current of 300 amperes this would give a gain of 300/2 = 150. Other GTO's may have gain of as high as $1 * 10^5$, this is more than any single standard switching transistor which converts into a greater power conversion efficiency. Under the Gate Drive Unit section Photos of the Anode Current and Gate Voltage will be shown. They can be compared with these waveforms.

B) The Gate Drive Unit [6]

There are two purposes for the gate drive unit. The first is to actually provide the power to "drive" the GTO on and off. The second is to provide isolation for the gate cathode junction from the rest of the circuitry. The gate cathode junction is where the connections for the on and off pulses are made. The timing comes from the PFN (pulse

General switching waveforms.

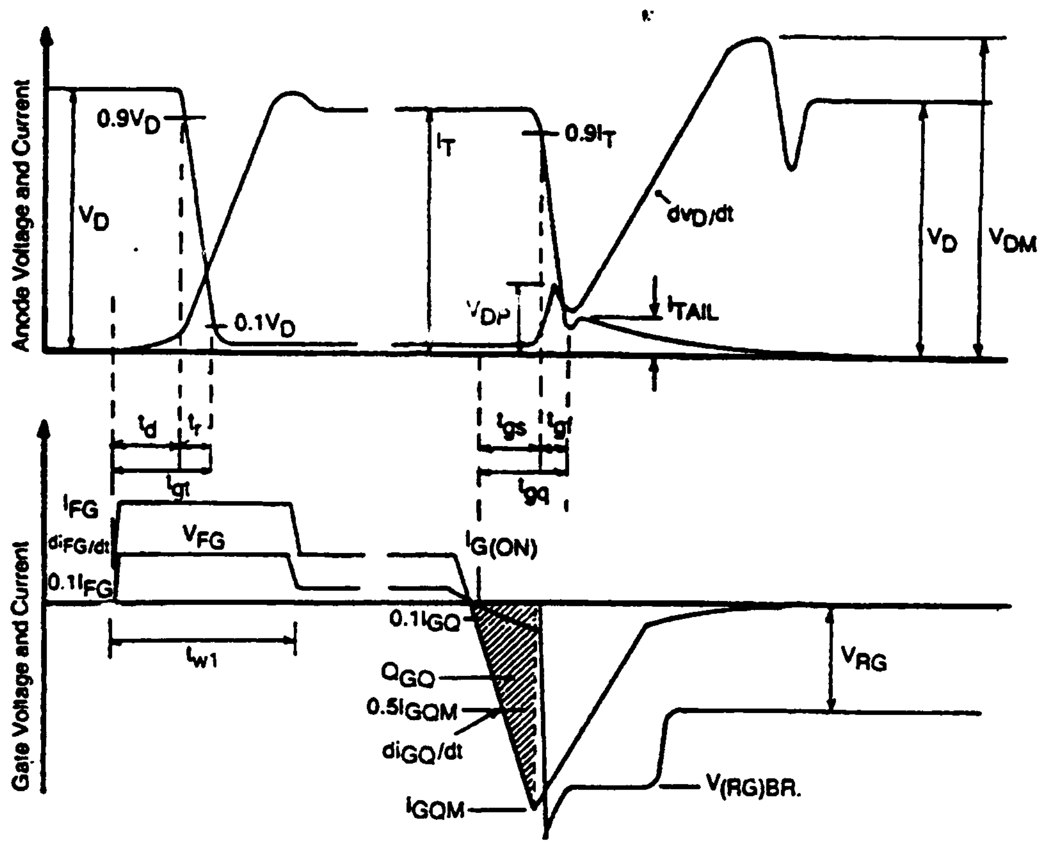


Figure 13

forming network) and is then amplified by the gate drive unit.

Figure 14 is the modified gate drive unit. The inputs are at the left hand side labelled "1ms pulse" (pin12) and "delayed 1ms pulse" (pin 11). Both are 5 volt level. The delay time is 1ms between the two 1ms pulses. The pulse width of each was chosen arbitrarily. The output of the gate drive unit will be a 1ms positive pulse (on pulse) and a 1ms negative pulse (off pulse) due to the delayed inputs. These on and off pulses are in Figure 15.

Referring back to Figure 14, the two input pulses are then fed into the first two NOR gates which make up an RS flip flop. The output pin 5, which is tied to pin 1 of the top NOR gate, gives a zero (0) voltage level (logic 0) for 1ms and a 5 volt level (logic 1) for 0.199sec. The period of the arc pulse is 0.2 sec. or 5 Hz.

The 4047 is a free running astable multivibrator. It generates 2 inverted pulses of 50kHz at its output pins 10 and 11. These inverted 50kHz pulses enter the second two NOR gates at pins 11 and 9. Pin 1, of the first two NOR gates, is now NORED with the pulses from the 4047. The result at the output pins 10 and 13 is that you have two inverted pulses at 50kHz in a pulse width of 1ms and 0 for 0.199sec. This means that when Q2 is on Q1 is off and when Q1 is on Q2 is off during the first 1ms. Then during the 0.199sec Q1 and Q2 are both off (see Figure 16). Q1 and Q2 are used to amplify the signal from the NOR gates. Q1 and Q2 act as a "push-pull" type of amplifier. The pulses are then sent through a "pulse transformer" after they are amplified by Q1 and Q2. If the

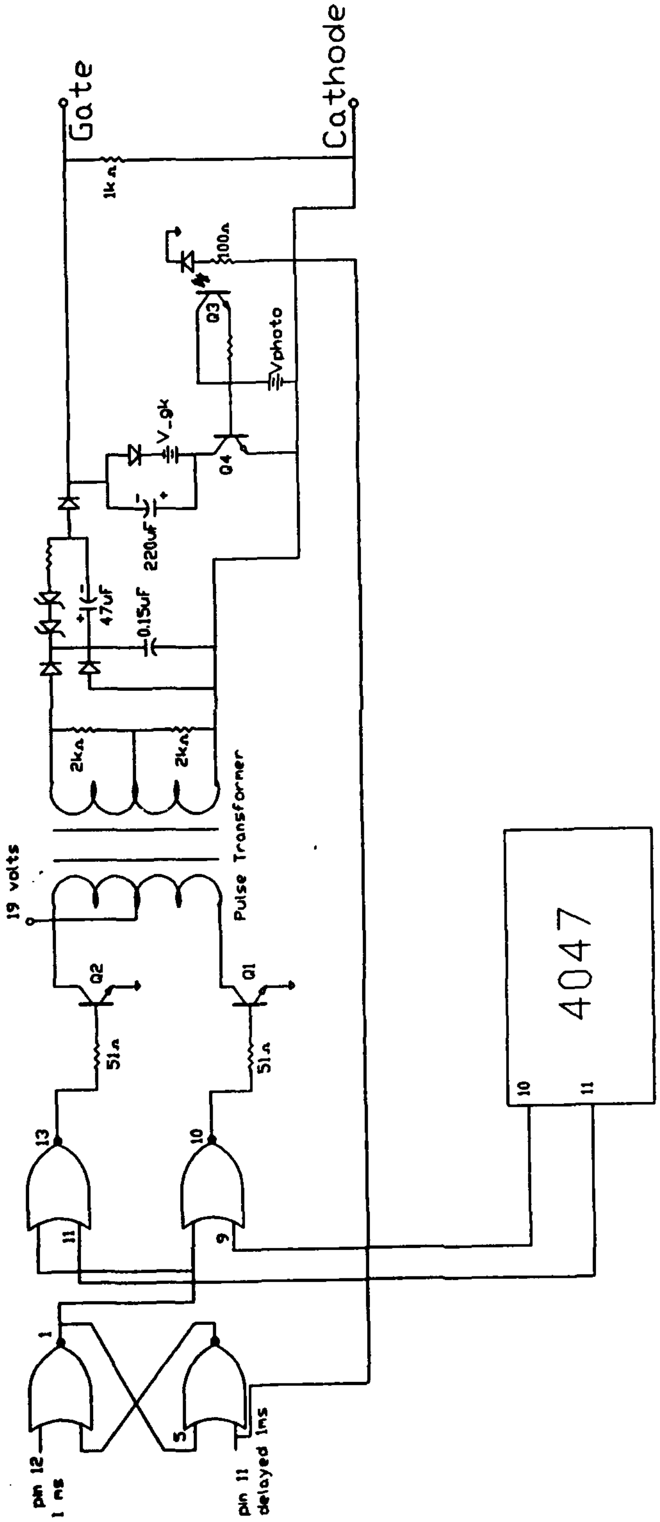

Gate
Cathode
1kΩ
100Ω
Q3
Vphoto
V_gk
Q4
220uF
47uF
0.15uF
2kΩ
2kΩ
Pulse Transformer
19 volts
Q2
Q1
51Ω
51Ω
4047
10
11
13
10
11
9
1
5
pin 12
1 ms
pin 11
delayed 1ms

Figure 14

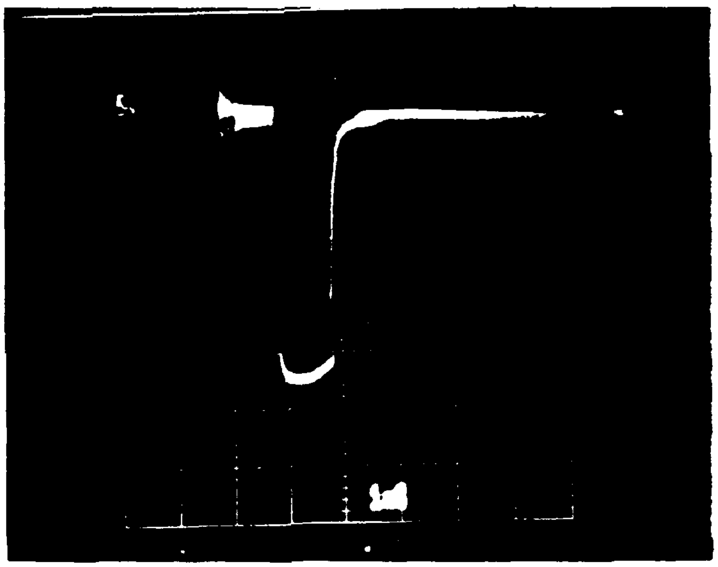


Figure 15

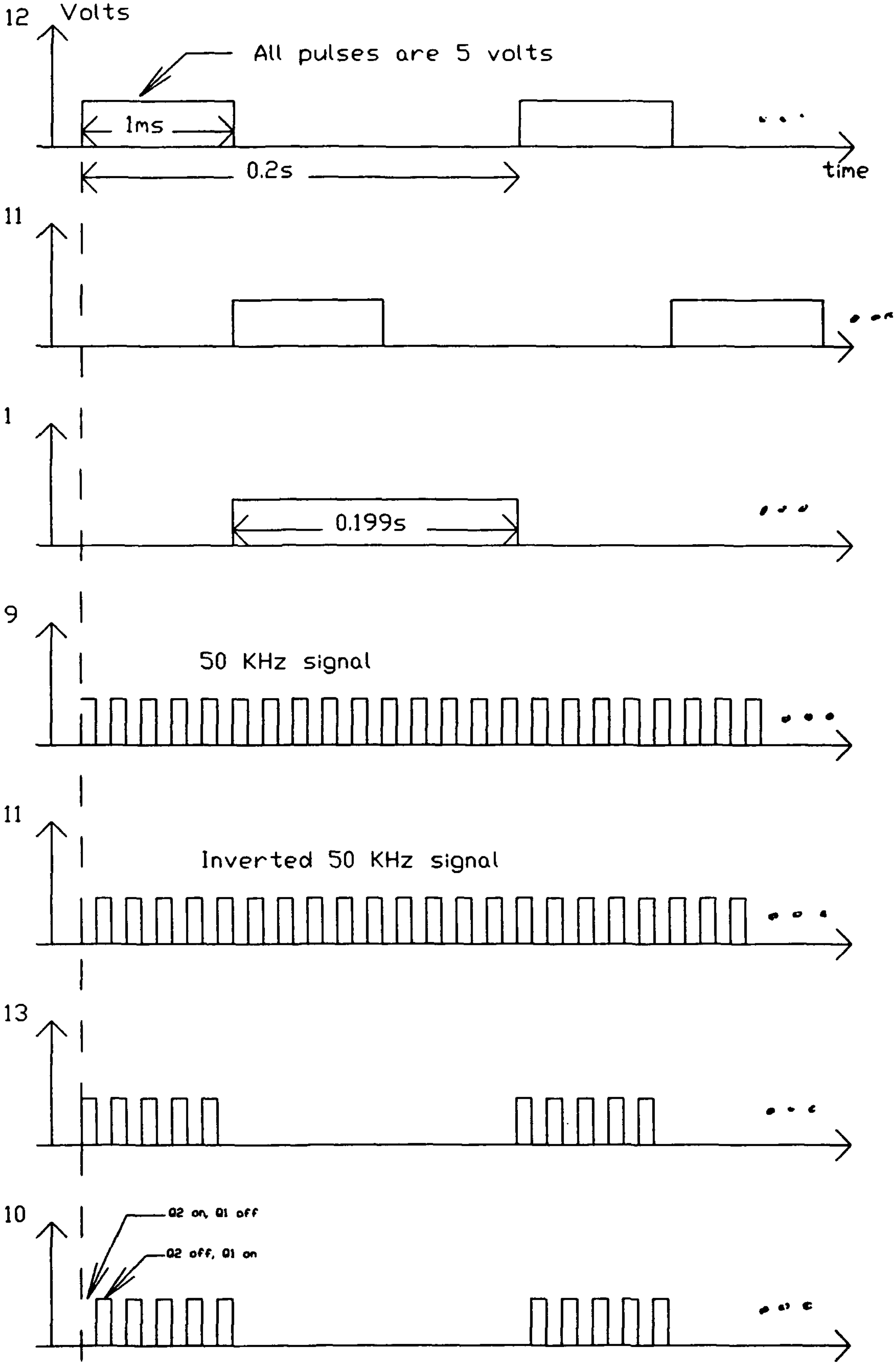

12
Volts
All pulses are 5 volts
1ms
0.2s
time
11
1
0.199s
9
50 KHz signal
11
Inverted 50 KHz signal
13
10
Q2 on, Q1 off
Q2 off, Q1 on

Figure 16

Volt sec product of the pulse is larger than the Volt sec product of the transformer the pulse on the secondary side of the transformer will be distorted because of the core of the transformer. That is why the pulse long 1ms pulse is broken up into a 50kHz pulse. The transformer itself is needed to provide isolation for the gate cathode junction. On the secondary side of the transformer is a center tapped full wave rectifier. This rectifier actually reconstructs the 1ms pulse from the 50kHz pulses. This 1ms pulse now charges up the 47uF capacitor which then discharges through the gate cathode junction (GK). This current that discharges from the capacitor turns the GTO on. The two existing transistors Q1 and Q2 had to be replaced with larger power transistors, and the pulse transformer also needed to grow in power. These were the start of the modifications. Next the turn off part of the gate drive unit needed to be modified.

In order to turn off the GTO the second 1ms pulse at pin 11 (delayed by 1ms) triggers a phototransistor (Q3) on which turns on transistor Q4. There is a 220 uF capacitor which has been charged up by an external power supply, V_gk. This 220 uF capacitor now discharges a negative pulse into the gate cathode junction to turn off the GTO. This whole part of the circuit was modified. The on and off gate voltage pulses are shown in Figure 15 and can be compared with the general switching waveforms in Figure 13.

Transistor Q4, which provides the high current to turn off the GTO, has a power dissipation of 150 watts, a maximum collector current of 15A and a gain of 120.

The external power supply, V_gk,sits at 55 volts. The power supply for the phototransistor sits at 19 volts and the power supply for Q1 and Q2 is also set at about 19 volts.

C) The Pulse Forming Network (PFN)

Figure 17a is a layout of the PFN. A 0.195sec pulse with a 0.2 sec period is generated at the 555 timer. This 0.195 sec pulse goes through an inverter to become a 5ms pulse with a 0.2 sec period and enters the gas pulse circuit and is also used to generate the two 1ms pulses which are delayed by 1 ms. Now the gas pulse is synchronized with what will be the arc pulse.

After the first inverter the 5ms pulse goes out to four places:

1. The gas pulse circuit (1)
2. A NAND gate (2)
3. Two inverters (3)
4. Two other inverters (4)

The gas pulse circuit (1) will be considered in the next section. The two inverters (3) are used as buffers before the pulse sees the RC network. The RC network is used to generate the first 1ms pulse. This pulse then goes through another two inverters used as buffers and enters the NAND gate (2) with the original 5ms pulse. It was found that the

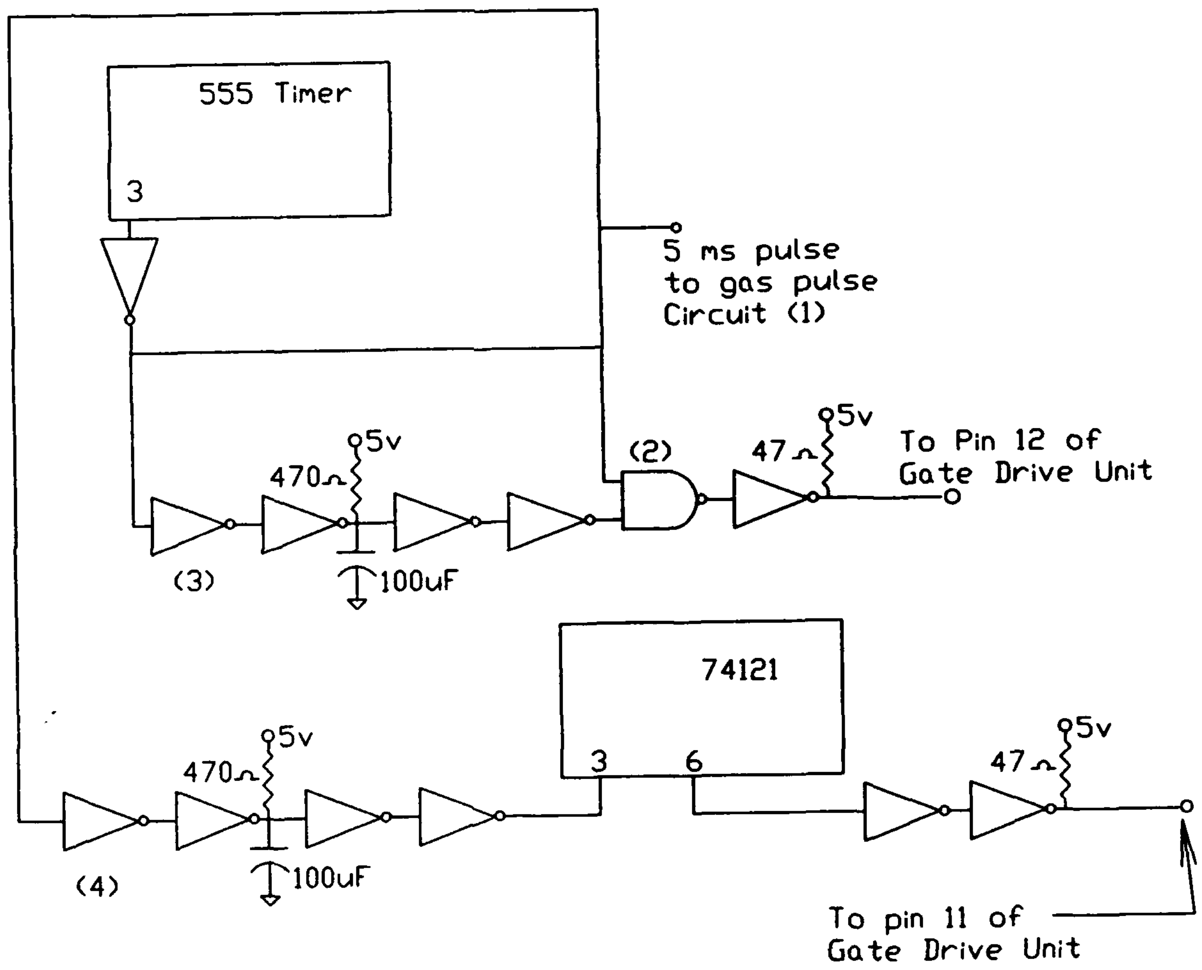

555 Timer
3
5 ms pulse
to gas pulse
Circuit (1)
5v
470Ω
(2)
47Ω
5v
To Pin 12 of
Gate Drive Unit
(3)
100uF
74121
5v
470Ω
3
6
47Ω
5v
(4)
100uF
To pin 11 of
Gate Drive Unit

Figure 17a

1ms pulse out of the RC network did not end at the same time as the 5ms pulse therefore by sending them both through a NAND gate they will be forced to end at the same time but the 1ms pulse would be inverted and become a 0.199s pulse therefore it is sent through one more inverter. This last inverter also boosts the voltage up to the required 5 volts by using a pullup resistor on chip 7406. This is now the first 1ms pulse which enters the gate drive unit at pin 12.

The 5ms pulse also goes through two other inverters (4) which act as buffers. Next it goes through an RC network and this now controls the delay instead of the pulse width by the use of the RC time constant. Now this pulse must have a width of 1ms. This is accomplished by using chip 74121 (Monostable Multivibrator). The 1ms pulse leaves chip 74121 at pin 6 and goes through two inverters which act as buffers. It then is boosted up to the required 5 volt level by the use of the pullup resistor on chip 7406. This delayed 1ms pulse now enters pin 11 of the gate drive unit. Figure 17b is a photo of both 1ms pulses delayed by 1ms, the period is 0.2s.

A photo showing the synchronization of the gas voltage pulse and the current pulse through a dummy load will be shown in the next section.

D) Gas Pulse Circuit

This circuit (Figure 18) is the same one used by Los Alamos National Labs to pulse their valve on. When the pulse is removed the valve shuts off. The 5ms pulse from

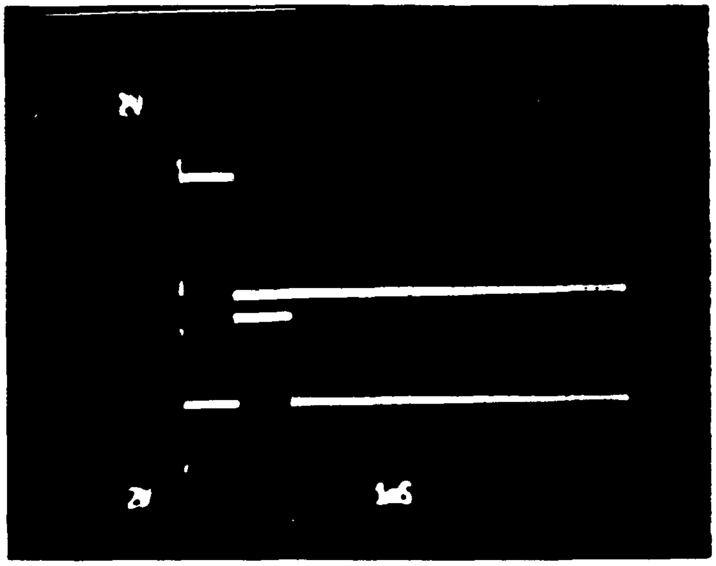


Figure 17b

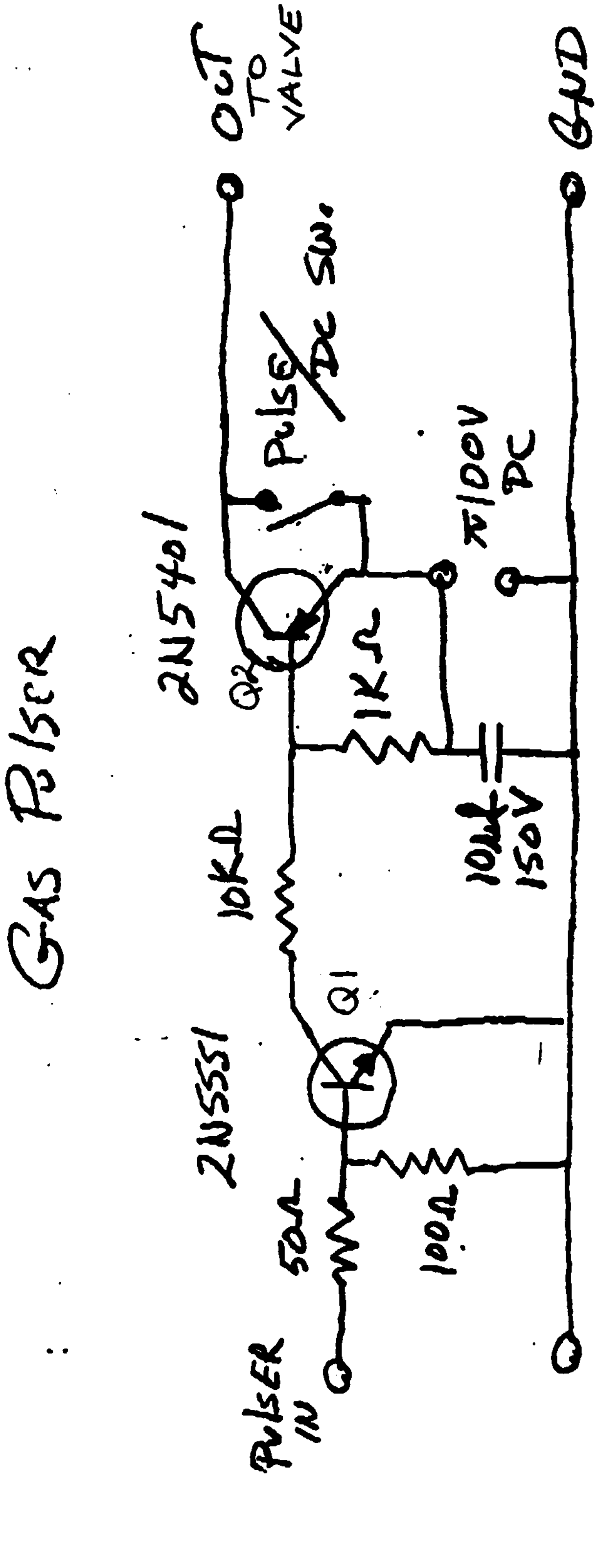

GAS PULSER
2N5401
Q2
2N5551
Q1
10KΩ
1KΩ
50Ω
100Ω
10µf
150V
+100V
DC
Pulse/DC Sw.
OUT
TO
VALVE
GND
PULSER
IN

Figure 18

the PFN enters the terminals marked "PULSER IN". If the input to the PULSER IN terminals is 0 volts and the switch marked "PULSE/DC SW." is open then, Q1 is off, Q2 is off and the 100 VDC power supply charges up the 10 uf capacitor. Now when the 5ms pulse enters the input terminals (PULSER IN), Q1 turns on, Q2 turns on, the 10 uF capacitor discharges through Q1 into the valve and then back into Q2. Once the 5ms pulse is gone the 10 uF capacitor starts to charge up again since Q1 and Q2 turn off.

If the switch "PULSE/DC SW." is closed then the 100 VDC power supply is placed directly across the valve which means the valve stays open whether or not the 5ms pulse is present at the input terminals. Figure 19 is drawing showing the width of the gas pulse and the arc pulse. It also shows the 4ms delay before the arc pulse arrives. Figure 20 is a photo of the gas pulse and what would be the arc pulse through a 1.5 ohm resistor.

Transistor Pulsing Circuitry

A) Characteristic Curves

Figure 21 contains V/I characteristics of 3 different transistors from a conventional curve tracer. The vertical scale is Collector Current in amperes. The horizontal scale is Collector-Emitter Voltage in volts. The Motorola MJ16020 transistor was determined to be the best choice of the three. Figure 22 are parameters for all three

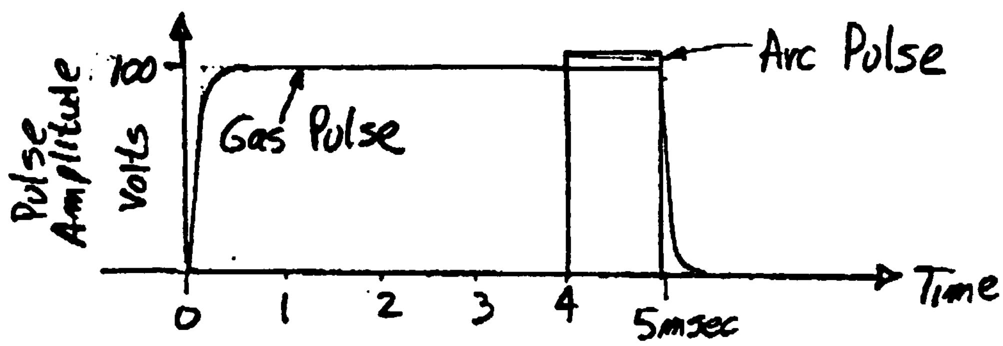

Arc Pulse
100
Gas Pulse
Pulse Amplitude
Volts
0
1
2
3
4
5msec
Time

Figure 19

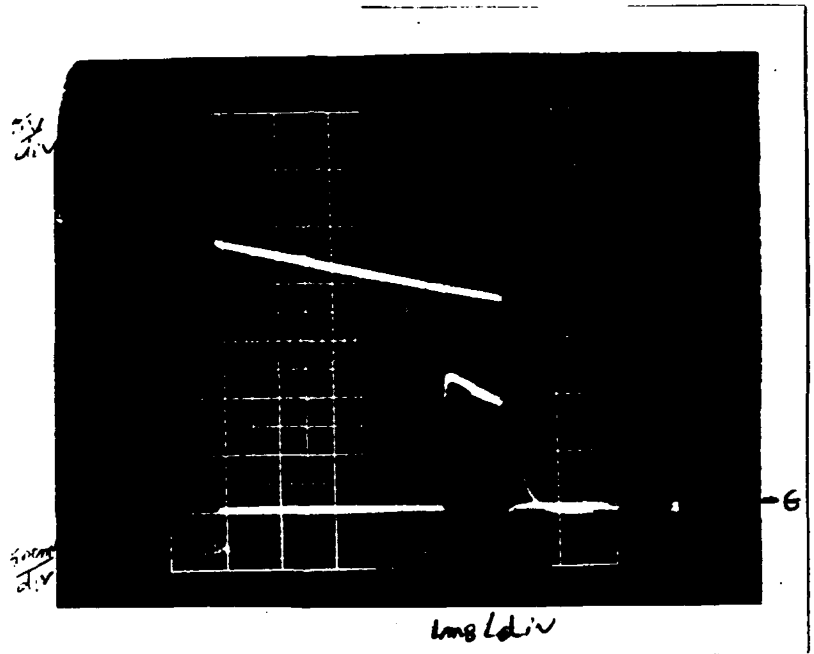
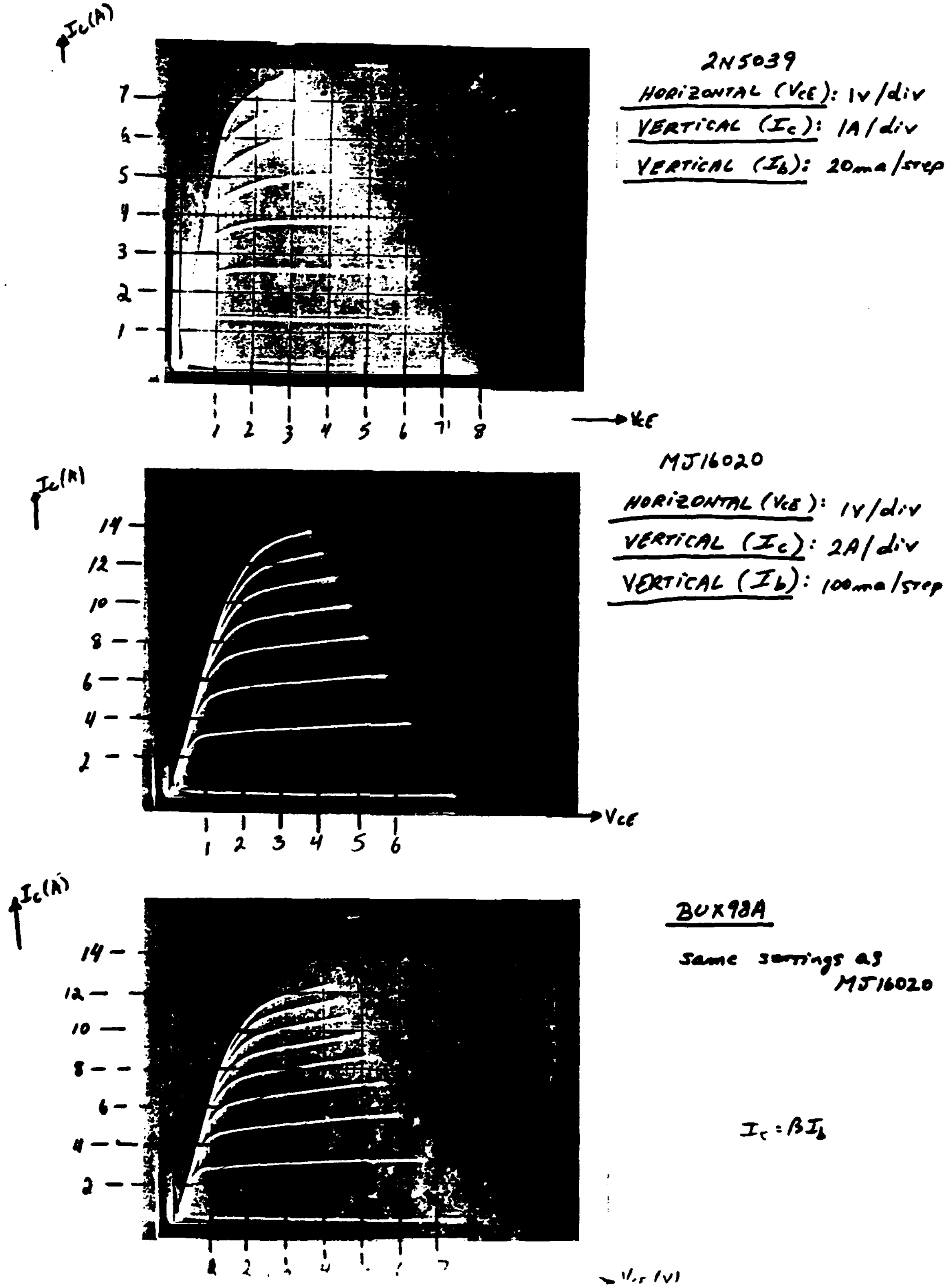


Figure 20



$I_c(A)$
2N5039
HORIZONTAL (V_{CE}): 1v/div
VERTICAL (I_c): 1A/div
VERTICAL (I_b): 20ma/step
V_{CE}
MJ16020
HORIZONTAL (V_{CE}): 1V/div
VERTICAL (I_c): 2A/div
VERTICAL (I_b): 100ma/step
V_{CE}
BUX98A
Same settings as MJ16020
$I_c = \beta I_b$

Figure 21

Bipolar Power Transistors

Device.............	MJ16020 c	@ IC (A).......	20
IC(cont) (A) max...	30	fT (MHz) min...	10 1
VCEO(sus) (V) min..	450	PD (W) @ 25°C..	250
hFE min............	5	Polarity.......	NPN
hFE max............	15 1	Package........	TO-204 (TO-3)
@ IC (A)...........	30	Material.......	Metal
ts (μs) max........	1.8	Price (100+)...	8.35
tf (μs) max........	0.2		

Bipolar Power Transistors

Device.............	2N5039	@ IC (A).......	10
IC(cont) (A) max...	20	fT (MHz) min...	60
VCEO(sus) (V) min..	75	PD (W) @ 25.C..	140
hFE min............	20	Polarity.......	N
hFE max............	100	Package........	TO-204 (TO-3)
@ IC (A)...........	10	Material.......	Metal
ts (us) max........	1.5	Price (100+)...	2.75
tf (us) max........	0.5		

Bipolar Power Transistors

Device.............	BUX98A (BUS98A)	@ IC (A).......	16
IC(cont) (A) max...	30	fT (MHz) min...	8
VCEO(sus) (V) min..	450	PD (W) @ 25.C..	250
hFE min............	8	Polarity.......	N
hFE max............	30 1	Package........	TO-204 (TO-3)
@ IC (A)...........	16	Material.......	Metal
ts (us) max........	3	Price (100+)...	
tf (us) max........	0.8		

Direct Replacement for BUS98A

Figure 22

devices.

By taking the source and putting it in the collector of the transistor we hoped to suppress the noise [10]. This would be achieved because looking into the collector one sees a very high (ideally infinite) AC impedance. This also means that the collector current can be modelled as a constant current source (Ic=Hfe*Ib). This constant current would force the current in the discharge to also become constant and the instabilities causing the noise would be suppressed.

Another way of explaining, this noise suppression technique, is to look at what happens to the AC collector current as it changes (see Figure 23) [4]. There must be an emitter resistor for this circuit to work properly as will be shown. All AC currents will be expressed as small letters.

1. ic increases (could be noise from source)
2. ie increases
3. ve increases (if there is an emitter resistor)
4. vbe decreases (since vb is constant)
5. ib decreases (ib=vbe/(hie+Re(1+B))
6. ic decreases to its original value

If Re was not present then ve would not be able to change since it would be tied to ground but ic and ie would still change. This is a type of feedback the transistor has and is used mostly to compensate for temperature changes in the transistor when it heats up.

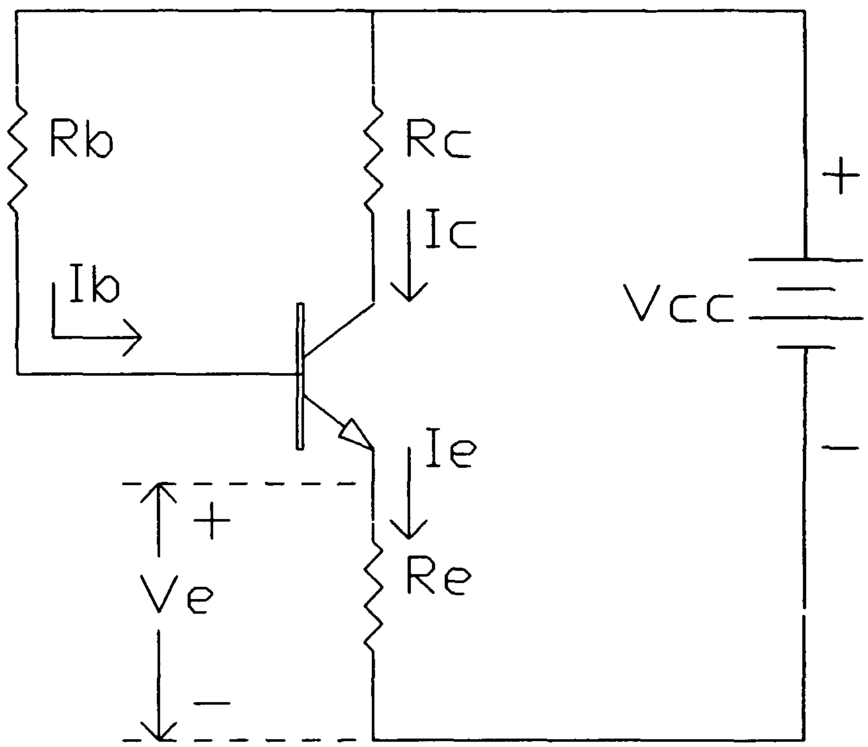


Figure 23

MJ16020 was chosen because it had the highest collector current rating, highest sustaining voltage from collector to emitter and largest bandwidth at 10MHz. The noise frequency in the Negative Ion Source is estimated to be about 1Mhz, therefore the transistor's bandwidth should be greater than the noise frequency in the source if the transistor is to have any effect.

B) Pulsing Circuit [10]

Although the MJ16020 has a collector current equal to 30 amperes, this is still much less than the required 150 amperes required to pulse the source. Five of these transistors were placed in parallel each taking close to 20 amperes with a dummy load of 1.5 ohms for testing purposes. The pulsing circuit is shown in Figure 24. The circuit contains 5 transistors in parallel. There is an overall emitter resistor of 0.8 ohms, we tried to keep this small to reduce power dissipation in the emitter however an emitter resistor was required if the feedback was to work effectively. The overall collector resistor consisted of a 0.05 ohm shunt (to view the collector current), a 1.5 ohm resistor simulating the Negative Ion Source, and 5-20 ohm resistors in parallel giving us a 4 ohm resistor. The overall collector resistance is $4+1.5+0.05=5.55$ ohms. At Ic = 100 amperes this would give a voltage drop of 7 volts across Vce if Ecc is equal to 642 amperes. On the V/I curves of MJ16020 this gives an Ic of approximately 20 amperes and 20*5 transistors = 100 amperes.

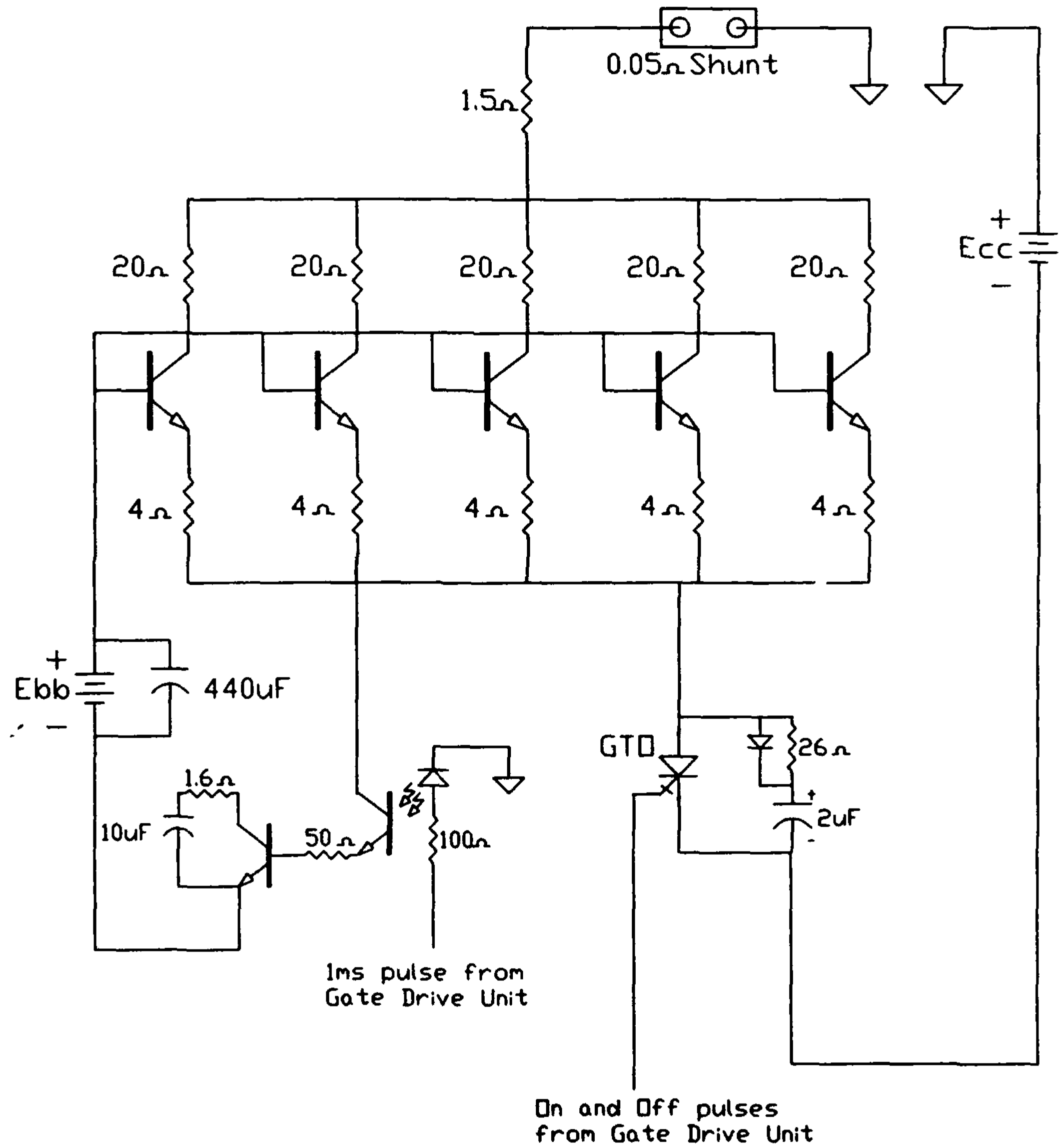

0.05Ω Shunt
1.5Ω
20Ω
20Ω
20Ω
20Ω
20Ω
+
Ecc
−
4Ω
4Ω
4Ω
4Ω
4Ω
+
Ebb
−
440uF
GTO
26Ω
2uF
1.6Ω
10uF
50Ω
100Ω
1ms pulse from
Gate Drive Unit
On and Off pulses
from Gate Drive Unit

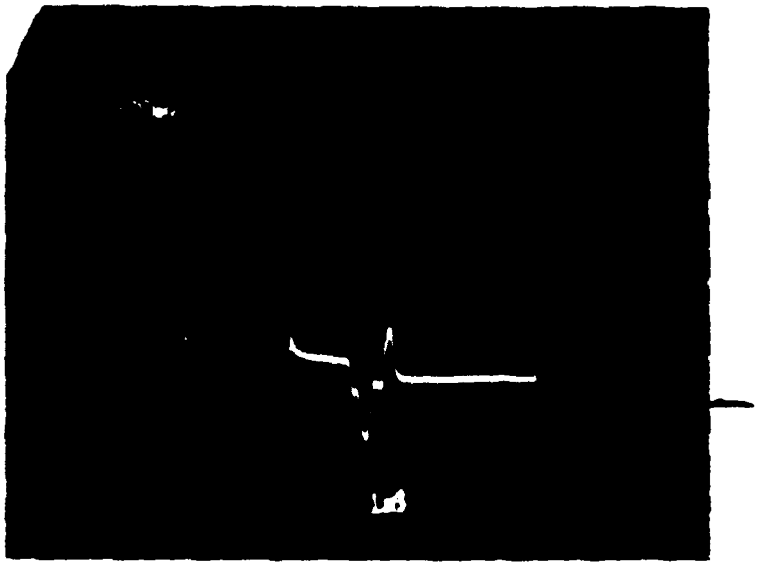
Figure 24

The GTO was placed in the emitter of the transistors and tied to the high voltage power supply Ecc. A separate 150 volt 50 ampere power supply was used to bias the base.

One problem which was encountered upon pulsing this circuit is that at Ic=10 amperes one of the main transistors would short out. This was due to the transistor switching off and the high di/dt was killing it [10]. The same type of snubber network used to protect the GTO could not be used to protect the collector to emitter junction because at high frequencies (where the noise is present) the capacitor would look like a short and defeat the purpose of the transistors. Another way to protect the transistors is to keep some base current flowing even when the collector current is turned off by the GTO. If we keep Ib flowing then the collector current will not turn off as fast killing the transistors. This is accomplished by taking the delayed 1ms pulse, (which turns off the GTO) entering the gate drive unit at pin 11, sending it through another phototransistor (NTE 3041), for isolation, then through another transistor (sk9040) for more gain and then to the base supply and the emitter of the main transistors. Now the pulse which turns off the GTO will also let some base current flow thereby not letting Ic drop as fast and protecting the transistor from the high di/dt which was present.

C) Pulsing Results

Figure 25 contains photos of Vce (0.5 volts) and Ve (25 volts). This Ve



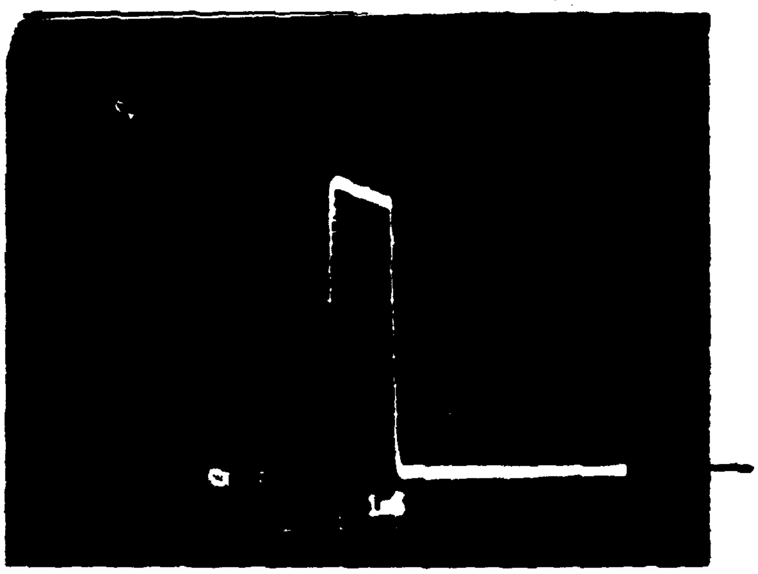


Figure 25

corresponds to an Ie (Ic) of approximately 25 amperes. This circuit was successfully pulsed to an Ic=80 amperes and a Vce of approximately 4 volts.

The procedure for increasing the voltage on the base and collector power supplies was:

1. Look at Vce and Ic (with the scope going into an isolation transformer)
2. Increase Ebb
3. Go to step 1
4. Increase Ecc
5. Go to step 1

It is very important not to increase either power supply too much or too fast.

Pulsed Discharge

A) Hollow Cathode Discharge [9]

Figure 26 is the circuit which was used to successfully pulse the Hollow Cathode discharge to 100 amperes. The GTO is in series with the discharge. A shunt is used to observe the current pulse. A voltage divider is used to observe the voltage pulse, the resistors in the divider were chosen so the voltage observed on the scope multiplied by 100 equalled the actual discharge voltage. A variable 100 ohm (max) resistor was used to vary the current. The resistance was set to 100 ohms for breakdown and then was

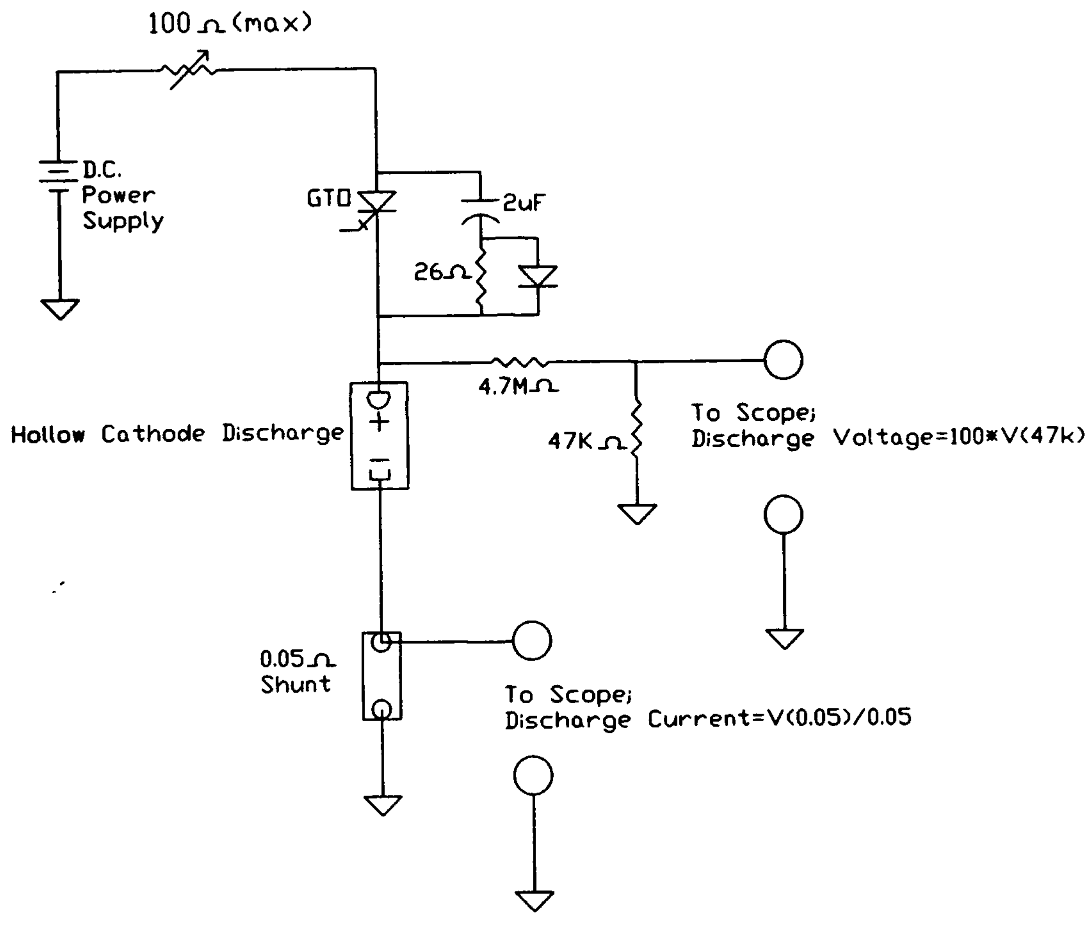

100 Ω (max)
D.C.
Power
Supply
GTO
2uF
26Ω
4.7MΩ
Hollow Cathode Discharge
+
−
47KΩ
To Scope;
Discharge Voltage=100*V(47k)
0.05Ω
Shunt
To Scope;
Discharge Current=V(0.05)/0.05

Figure 26

decreased to increase the current.

Figure 27 contains two photos of the discharge voltage and current. The top photo (Figure 27a) is set to a 500us scale. The pulses are each 1ms in width. The current pulse has a value of 50 amperes and the voltage pulse has a value of 50 volts.

Figure 27b is much more interesting. Here, two regions are visible in the Hollow Cathode discharge. One at 50 amperes and about 320 volts and another region at about 72 amperes and 200 volts. What is occurring is that the negative glow is moving within the hollow of the hollow cathode which leads to a further increase in current. Much research have been done on this and is still going on now in trying to understand this "Hollow Cathode Effect". The Hollow Cathode Effect is also pressure dependent, meaning as the pressure changes the glow could also move in the hollow cathode causing the current to increase dramatically.

B) The Negative Ion Source

The Negative Ion Source still has not been successfully pulsed. Many attempts have been made. The problem is still under investigation. Pulsing was first attempted without the heaters or the Cesium or the magnets needed around the slit. First the magnets were added with no success. Then the heaters were connected and the Cesium was placed on the cathode surface. However too much Cesium was added, although the source did pulse 5 or 6 times in the matter of a minute it was concluded that the arc

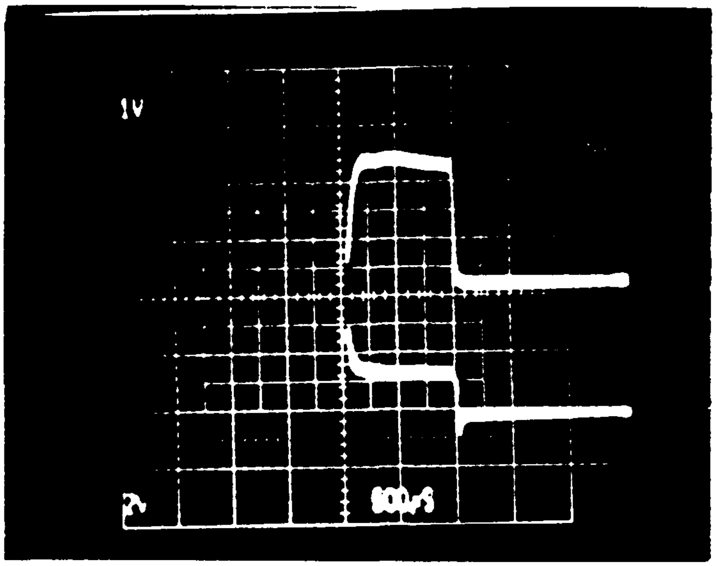


Figure 27a

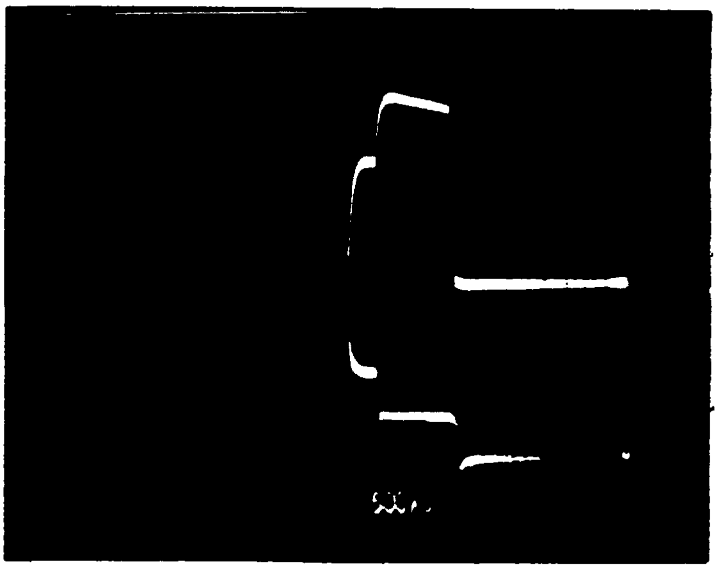


Figure 27b

pulse was conducting through the Cesium instead of the gas. When less Cesium was used the discharge still did not pulse.

The Negative Ion Source pulsing circuit is in Figure 28. In this case the anode is grounded (for safety) where as in the Hollow Cathode the cathode was grounded.

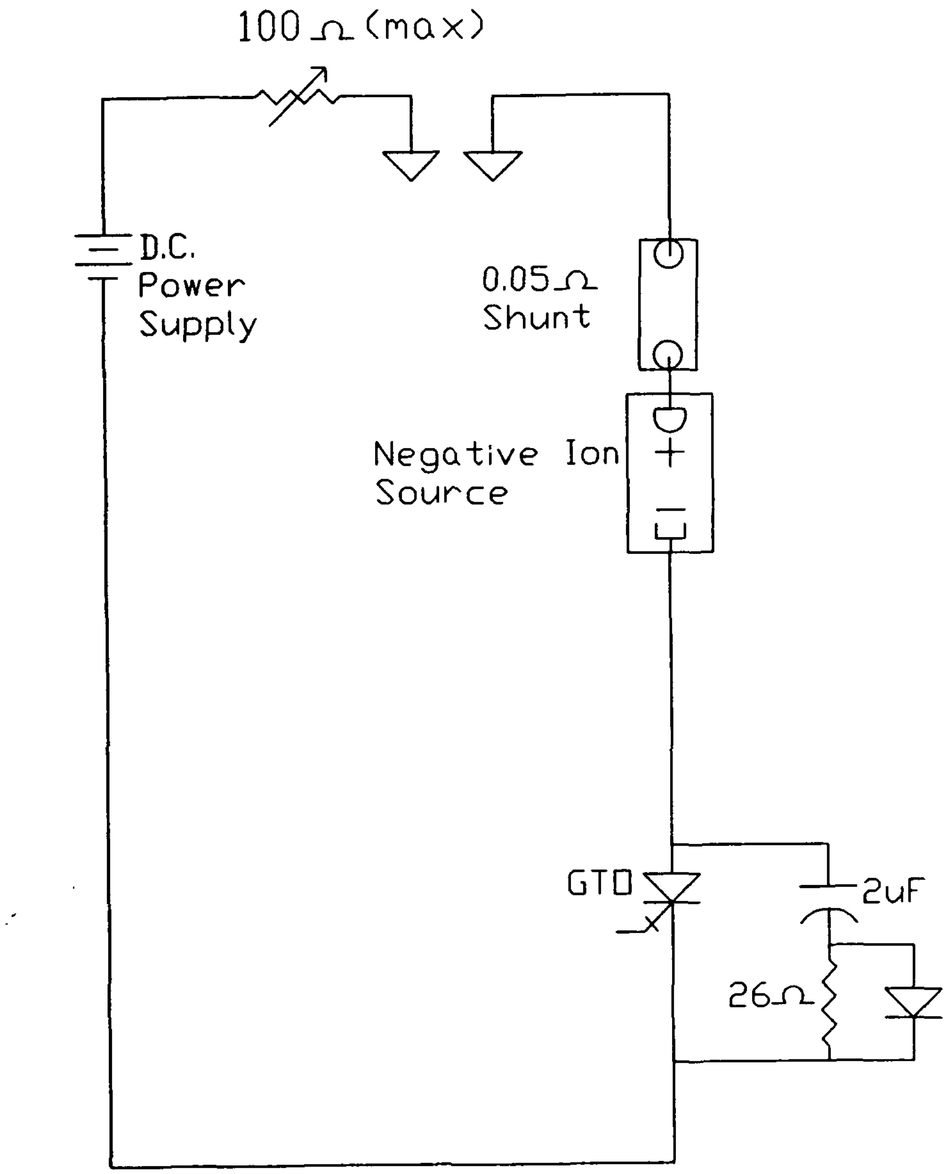

100 Ω (max)
D.C.
Power
Supply
0.05 Ω
Shunt
Negative Ion
Source
+
−
GTO
2uF
26 Ω

Figure 28

Conclusion

The GTO pulsing circuit has been tested on a 1.5 ohm resistive load and on the Hollow Cathode discharge. A PFN was constructed for a gate drive unit. An existing gate drive unit was modified for a high power GTO. A transistor circuit has been pulsed to 100 amperes with a 1.5 ohm load.

The next step is to most importantly pulse the Negative Ion Source. After the Negative Ion Source has been pulsed alone and the noise is present, the transistor circuit needs to be pulsed with the source in the collector leg of the transistors to see if the transistors can suppress the instabilities in the source which are causing the noise.

References

[1] Brown, Ian G., "The Physics and Technology of Ion Sources", John Wiley & Sons, New York, 1989.

[2] Diefenderfer, A James, "Principles of Electronic Instrumentation", Saunders College Publishing, Philadelphia, 1979.

[3] Mauro, R., "Engineering Electronics: a practical approach", Prentice Hall, N.J., 1989.

[4] Losco, Brother Michael, "Transistor Bias Circuit Design", Manhattan College, N.Y., 1986.

[5] Albrecht, A.P., Davis, D.C., Landee, R.W., "Electronic Designers Handbook", Mcgraw Hill Book Co., 1957.

[6] Joshi, P.N., "Pulse Width Modulated AC Motor Control Using GTO's", Engineer's Design Project, Polytechnic University, June 1990.

[7] Cheo,B., Kirkici,H., and Bruno, D., "Investigations of the Transient Behavior of the Cathode Fall Region in Planar and Hollow Cathodes", Annual Report, POLY-WRI-1580-90, 1989-1990.

[8] Marconi Circuit Technology Corp., Farmingdale, N.Y.

[9] Bruno, D., "Properties of a Segmented Hollow Cathode Discharge", Masters Thesis, Polytechnic University, June 1991.

[10] Gray, Paul R., Meyer, R.G., "Analysis and Design of Analog Integrated Circuits", Wiley, N.Y., 1984.

[11] Powerex Power Semiconductor Data Book, Powerex Inc. 1988

[12] Rashid, M.H., "Power Electronics: Circuits and Applications", Prentice Hall, 1988.

[13] Hayt, William, "Engineering Circuit Analysis", McGraw Hill, 1978