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TELEC LASER EXPERIMENT

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1.0 SUMMARY

An experimental Thermoelectronic Laser Energy Converter (TELEC) was recently constructed and tested at Ames Research Center with a 40 kW combustion laser operating at a wave length of 10.6 μ. The objective of the test was to demonstrate the feasibility of the TELEC concept for converting a laser beam into electric power. The TELEC System is intended as the receiver for a laser power transmission system in space.

1.1 Description of the Concept

The TELEC is a high power density plasma device which absorbs an intense laser beam by inverse bremsstrahlung with the plasma electrons. A high beam intensity ($\geq 10^4$ watts/cm^2) is required to maintain a high electron temperature and sustain the plasma while producing output power. The favored configuration of a TELEC requires a narrowly focused collimated beam with a long optical path ($\gtrsim 10$ m) in the plasma to absorb nearly all of the beam energy. Suitable optics (mirrors and/or lenses) to concentrate and collimate the beam will be required on the receiver spacecraft. The system must also include a chamber with windows that are transparent to the laser radiation to contain the plasma gas.

Operation of the TELEC as an energy converter may be thought of as a heat engine whose peak cycle temperature is the electron temperature in the plasma. Since the electron temperature is very high ($\gtrsim 10^4$ °K), the Carnot efficiency is nearly 100%. The energetic electrons diffuse out of the plasma striking two electrodes which are in contact with the plasma at the boundaries. These two electrodes have different areas: the larger one is designated as the collector, the smaller one is designated as the emitter.

Most of the electrons diffusing out of the plasma strike the surrounding collector surface causing it to become negatively charged. This generates an EMF in the external circuit. Since more electrons are collected by the larger area of the collector than by the emitter, there is a net transport of charge even though the current flows in opposition to a potential difference. The smaller electrode functions as an electron emitter to provide continuity of the current. Waste heat is rejected from the collector electrode.

Positively charged ions also flow out of the plasma and those striking the collector neutralize part of the output current. However, because the mobility of the ions is much smaller than the mobility of the electrons ($\mu_i \approx 1/500\ \mu_e$), and because of ion reflection at the boundaries, the ion currents are believed to be small and probably would not consistute a serious loss.

1.2 Description of the Experiment

The laser beam is transmitted into a chamber containing cesium vapor at pressures of 2 to 5 torr and produces a plasma around the TELEC electrodes. Salt windows (NaCl) are used to transmit the laser beam into the cesium chamber. However, before the test, a chemical reaction between the salt and the cesium vapor caused the windows to become nearly opaque or "severely frosted". The chemical reaction was believed to be a result of metal oxides and water vapor present in the chamber because of an earlier vacuum leak.

To avoid the reaction with salt windows, the experimental chamber was cleaned up, rebuilt, and modified to eliminate the leaks and to permit active pumping. The Cs vapor was admitted just before operation with the laser. However the reaction with the salt windows again occurred immediately on contact with Cs vapor. Despite degradation of the window surfaces, the windows survived 9 laser beam exposures (~ 1/2 sec duration) until the windows were deliberately broken on the 10th and final run. Although the laser beam could be transmitted through the windows, a large amount of scattering and/or attenuation resulted from the "frosted" window condition.

The experiment was performed in the path of the beam with an approximately F-12 convergent optics. The total angle of beam convergence is 4.5°. The converging beam just barely grazes the TELEC electrodes at a distance of 13 cm from the focal point. The laser beam was admitted to the chamber for only a short duration controlled by a mechanical shutter.

1.3 Summary of the Results

Plasma Production - A stable conducting plasma in the cesium vapor was produced and maintained by the laser beam in all but one of the runs. A short duration current pulse was applied to the electrodes to initiate ionization on some of the runs. However, the beam self-initiated the plasma without a pulse on other runs. These results are encouraging since the beam intensity coming through the frosted windows was believed to be very near the minimum threshold for plasma maintenance.

Electric Output - Currents of 1-10 amperes were obtained while the TELEC voltage was being swept with an external power supply. On all but the last run, no current was obtained with a power producing voltage greater than 1 volt. Although this is a reasonable result with a low beam intensity, the output with voltage less than 1 volt does not preclude a thermionic converter effect which could have occurred with beam heating of the electrodes.

Final Run Performance - To avoid the beam attenuation of the frosted windows, it was decided to burn through the windows with the beam on the final run. This permitted the beam to enter the TELEC cell at full intensity. However, the cesium vapor escaped through the hole in the window, thus terminating the experiment. Nevertheless, data was obtained during the last run while Cs vapor was escaping; and a current of several amperes at ~ 3 volts was observed. This value agrees with the detailed theoretical calculations. Unfortunately the value is doubtful because it is likely that some plasma current was conducted to the metal chamber and may have given an incorrect current reading.

2.0 TEST VEHICLE FABRICATION

2.1 Window Designs and Preliminary Tests

Although TELEC operation is possible in other gases, the highest performance predicted by detailed theoretical calcuations requires cesium as the medium for the plasma. Thus, at the beginning of the project, a search was carried out to find a suitable window material which would transmit the CO_2 laser beam at 10.6 μ and be compatible with cesium vapor. One of the materials investigated as a possible window was zinc selenide. However, it was found that this material reacts with cesium vapor, turns into a black powder, and thus is not suitable. Consultation with Harshaw Chemical Company regarding alkalai halide crystal windows indicated that some of these crystals should be compatible with cesium vapor and capable of the elevated temperatures necessary for operation in the TELEC chamber. At the recommendation of the personnel at Harshaw Chemical Company, and because of economic considerations, sodium cloride was selected as a candidate window material. Small test windows (~ 2 cm diameter) were then obtained as samples for preliminary tests.

No suitable way was found to make a seal to the sodium cloride material which would make a vacuum tight joint and would be impervious to cesium vapor. Consequently, it was decided to design a chamber with two-stage windows. The outermost windows would have O-ring seals which provide vacuum tight closures and present air from getting into the system. These O-ring seals would be maintained at a low temperature (~ 50°C) by water cooling. Inside the outer windows, a secondary set of windows, which would contact the cesium vapor itself, would be used. The inner windows are not sealed to the chamber. Instead these windows are pressed mechanically into intimate contact with lapped metal surfaces giving an approximate seal which maintains a tolerably small loss rate of cesium vapor. The inner windows and the lapped "seals" must be maintained at a temperature above the cesium reservoir temperature (~ 300 to 400°C).

Mechanical tests with the small sample salt windows showed that an acceptably low leak rate could be obtained by the mechanical pressure against a smooth metal surface. Tests in cesium vapor for up to 3 days showed no degredation of the window surfaces. As a result, the design for a test chamber was completed and the chamber was constructed as shown in Fig. 1. The test chamber contains a double set of windows at both ends. The laser beam is brought into the system, passed through the TELEC electrodes, and then exits through the second set of windows at the rear end of the test chamber.

2.2 Electrode Design

The original concept for the electrodes in a TELEC cell are as shown in Fig. 2. This concentric cylindrical configuration was chosen to approximate the mathematical model used for theoretical calculations. It was also planned that the center emitter rod could be resistively heated by passing a current through the rod. This would permit operation of the cell as a thermionic converter before its operation as a TELEC device with the laser beam. The work function of the electrodes could be determined in

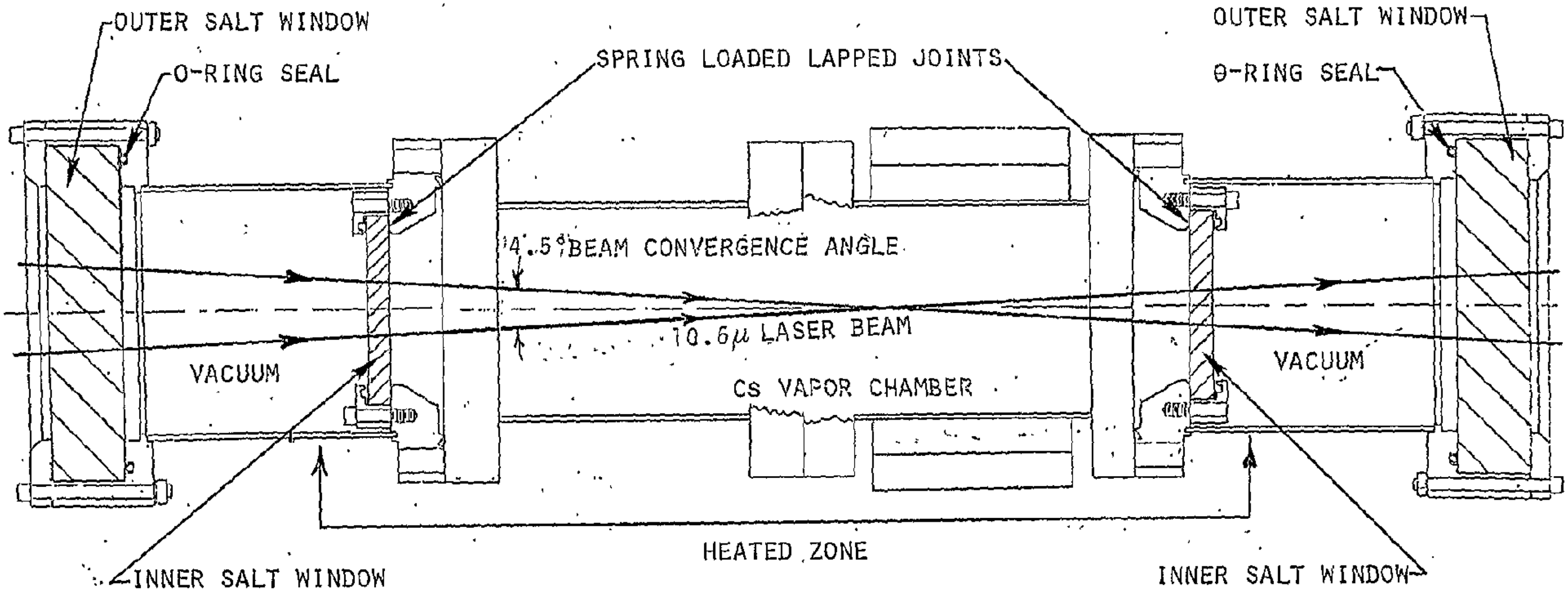

Fig. 1 Double Window Design for the TELEC Test Chamber

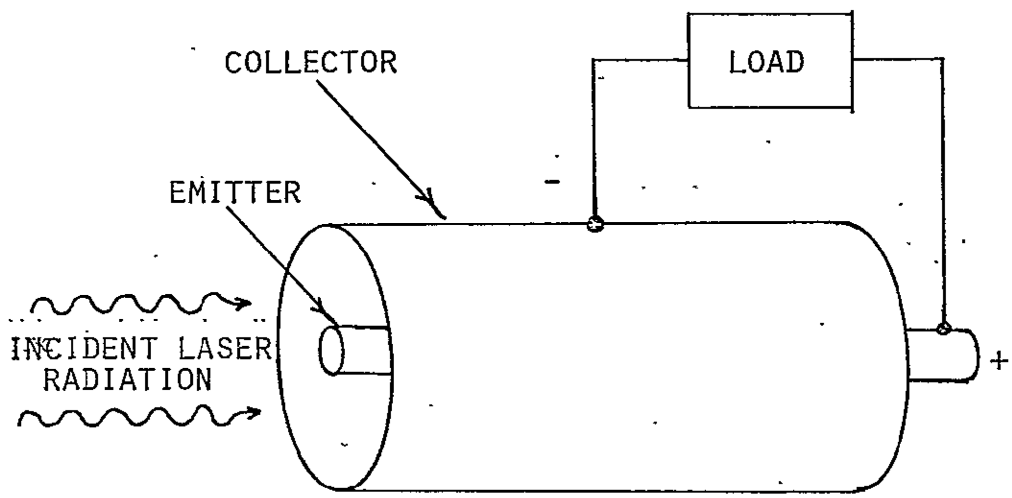

Fig. 2 Elementary TELEC Configuration

cesium vapor in this way with preliminary testing. Any deviations from the performance as a thermionic converter caused by the addition of the laser radiation could be attributed to TELEC affects and distinguished from thermionic behavior.

A set of mock-up electrodes with a resistively heated emitter rod (1 mm Dia. tungsten) and a concentric collector (1 cm ID molybdenum) was constructed. These electrodes were then installed in a mock-up test chamber which was filled with argon. The mock-up chamber contained no windows. Argon was purged through the chamber and allowed to flow out of the beam entrance aperatures during the tests. The mock-up was exposed to the laser beam to determine the feasibility of the electrode design. It was found that the laser beam destroyed the central emitter rod under all of the test conditions. Consequently, this geometry was abandoned.

A second type of emitter design using a tungsten blade which barely contacts the outer edge of the laser beam was tried in the mock-up. The mock-up tests indicated that an emitter electrode of the blade type could survive a beam intensity up to 42 kW for 2 seconds duration with no significant damage. However, the thickness of the emitter blade and distance of protrusion into the laser beam are crucial parameters for the blade survival. The blade with a thickness of 1 mm and a protrusion depth of 1.1 mm was found to be adequately resistant to damage by beam impingement. A heat transfer analysis showed that the temperature of the blade tip reaches thermodynamic equilibrium in substantially less than 0.1 second. Consequently, it was felt that this emitter geometry would be suitable for the TELEC cell.

A final set of TELEC electrodes were designed using a tungsten blade emitter and a split block molybdenum collector. These electrodes can be seen from the beam input end in Fig. 3. The blade emitter is at the top of the photo and protrudes a short distance into the one centimeter diameter circular opening between the split halves of the collector block. The TELEC electrodes were assembled and installed in the stainless steel cesium chamber as shown in Fig. 4. Separate current connections and voltage probes were provided for each of the collector halves and the emitter as can be seen in Fig. 4. A drawing of the electrodes mounted in the TELEC chamber is shown in Fig. 5. Two views of the TELEC test apparatus can be seen in Figs. 6 and 7. Connec-

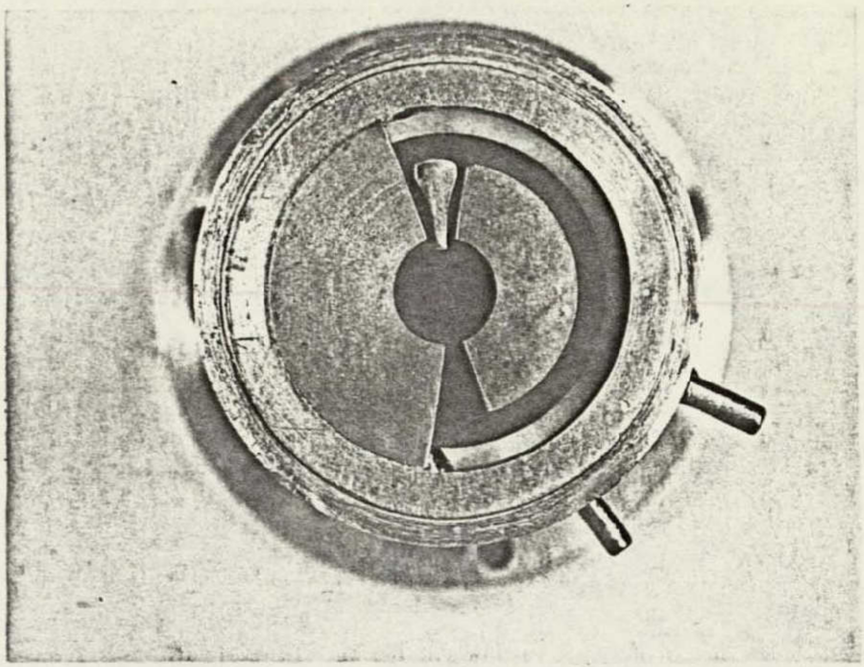

Fig. 3 TELEC Electrodes (seen from beam input end)

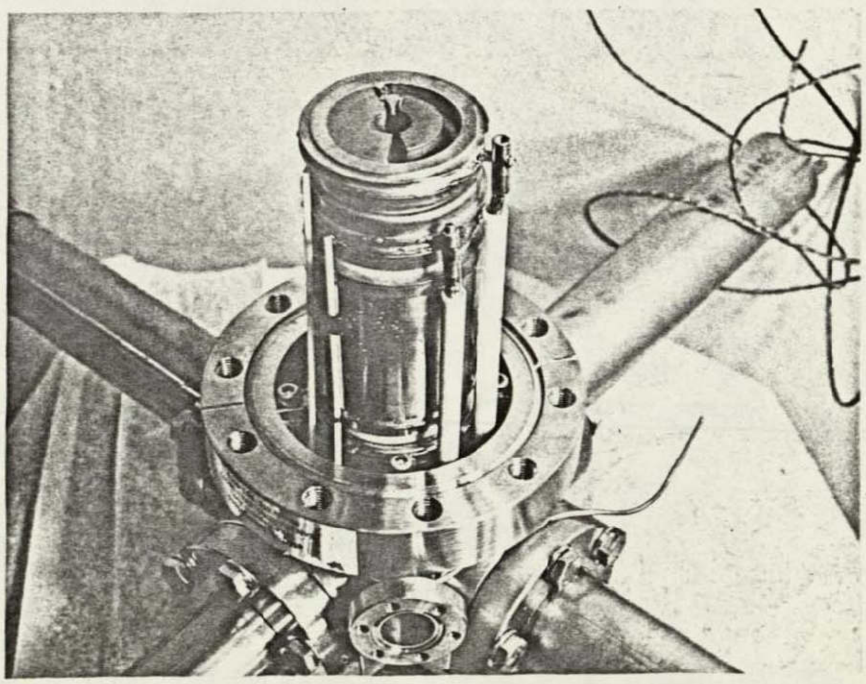

Fig. 4 TELEC Internal Parts Mounted in Test Chamber

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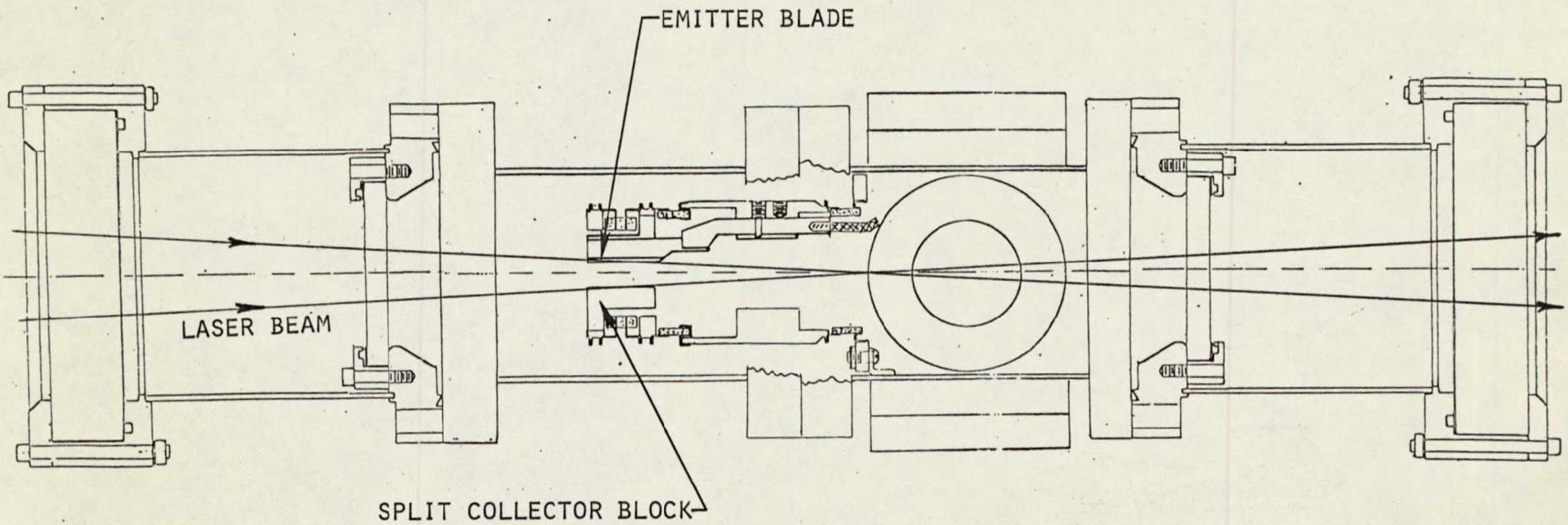

Fig. 5 Drawing Showing Location of TELEC Electrodes in Test Chamber

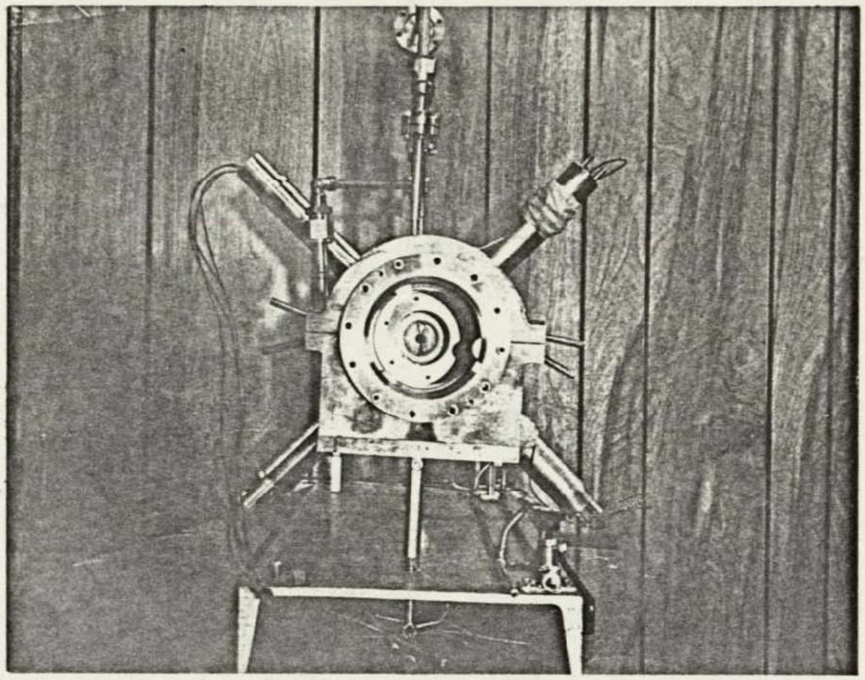

Fig. 6 End View of TELEC Test Apparatus

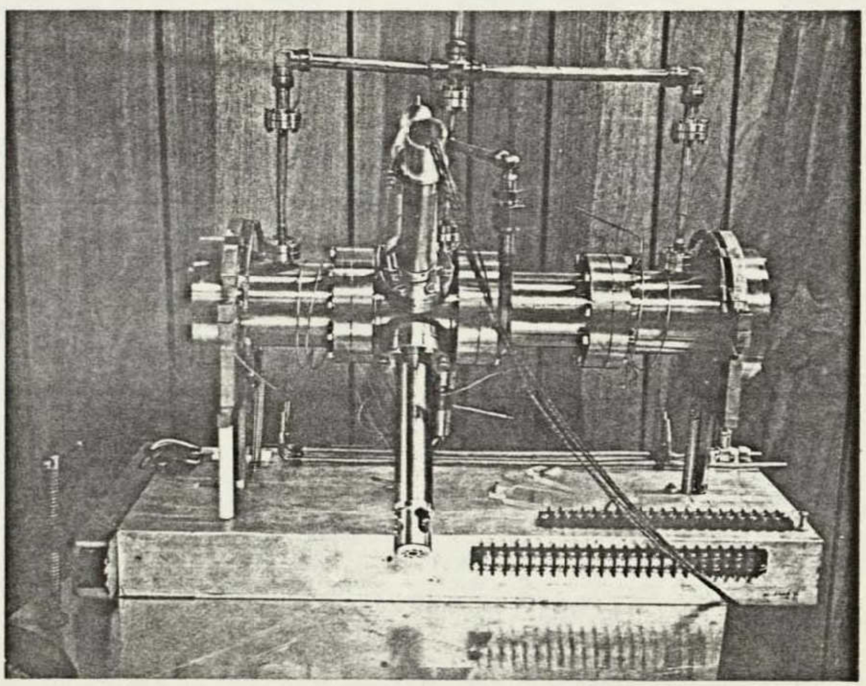

Fig. 7 Side View of TELEC Test Apparatus

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The TELEC chamber was disassembled, completely cleaned, and fired at high temperatures in hydrogen to remove all metallic oxides. The system was then rebuilt with a different type of vacuum system which had no pinch-offs and allowed a continuous pumping of the chamber up to the point of operation. Instead of a pinch-off, a hot valve was installed between vacuum plumbing and the rest of the cesium chamber. Based on the results of the chemical analysis these measures were expected to eliminate any further fogging of the salt windows. A further precautionary measure was taken in the way that the cesium distillation was handled; cesium was not distilled into the system until after it had been installed in front of the laser beam and was ready for immediate testing with the laser. On the previous initial attempt the cesium distillation was done several days prior to transportation to the laser testing site.

3.2 Window Behavior During Laser Beam Testing

After the system was installed in the laser beam optical path and the cesium was distilled into the chamber for the second time, immediate fogging of the inner salt windows was observed as the vapor was admitted, despite the remedial measures taken to prevent interaction with the windows. Apparently the reaction between the salt and cesium does not require the chemical cycle described previously. In fact the reaction on this second occurence appeared to be even more rapid than it was the first time.

Although it was expected that the laser beam could not be transmitted through the opaque windows, the IR transmission of the fogged salt window was unknown. It was decided to try to expose the windows to the laser beam and, fortunately, the transmission of the 10.6 μ laser beam was still adequate to carry out some experimentation. Enough of the beam energy was transmitted through the frosted salt windows to prevent them from being damaged by the laser beam. Nine beam exposures of approximately 1/2 second duration were given to the salt windows without damage. During the early runs it was possible to determine that some of the laser beam was transmitted completely through the cell as evidenced by burn patterns on asbestos plates placed at the rear of the test chamber. However, a large amount of beam scattering and/or attenuation did result from the frosted windows.

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The condition of the windows caused the beam intensity in the region of the TELEC electrodes to be unknown during the experiments. The intensity inside the cell was no doubt considerably less than the incident intensity available before the beam entered the chamber. However sufficient beam energy was transmitted into the cell to allow plasma formation and some TELEC operational information was obtained.

4.0 TELEC TESTS PERFORMED WITH THE AMES COMBUSTION LASER

4.1 Experimental Set-Up

The TELEC apparatus was installed in the optical path of the Ames laser with the beam reflected from a converging off-axis mirror as shown in Fig. 8. The beam diameter at the location of the mirror was approximately 18 cm. The TELEC electrodes were located 212 cm from the mirror. The beam focus occurred behind the electrodes within the cesium chamber at approximately 225 cm from the mirror. The diameter of the beam as it enters the TELEC electrodes just contacts the split collector block and the emitter blade (see Fig. 5).

Electric heaters were attached to the TELEC chamber to maintain the complete chamber above the reservoir temperature of the cesium vapor. Controls and power lines for these heaters were all fed outside the target room to an external control system. Fifty temperature sensing thermocouples were also cabled out of the target room to monitor the temperatures over the TELEC chamber. Special thermocouples mounted within the split halves of the molybdenum collector were tracked on chart recorders to show the temperature rise in the electrodes while the beam was admitted.

The electrical circuit for the TELEC system itself is shown in Fig. 9. Separate current measuring shunts are provided for each half of the collector and for the emitter blade. Separate voltage probes for each of these electrodes are brought out of the Cs chamber through insulated feedthroughs. The two halves of the collector are connected in parallel and to a voltage sweep power supply. The power supply is a programmable bipolar unit which is driven with a signal generator to provide a sinusoidal variation of the potential on the TELEC electrodes. All three current signals from the shunts and the voltage difference between the emitter and one half

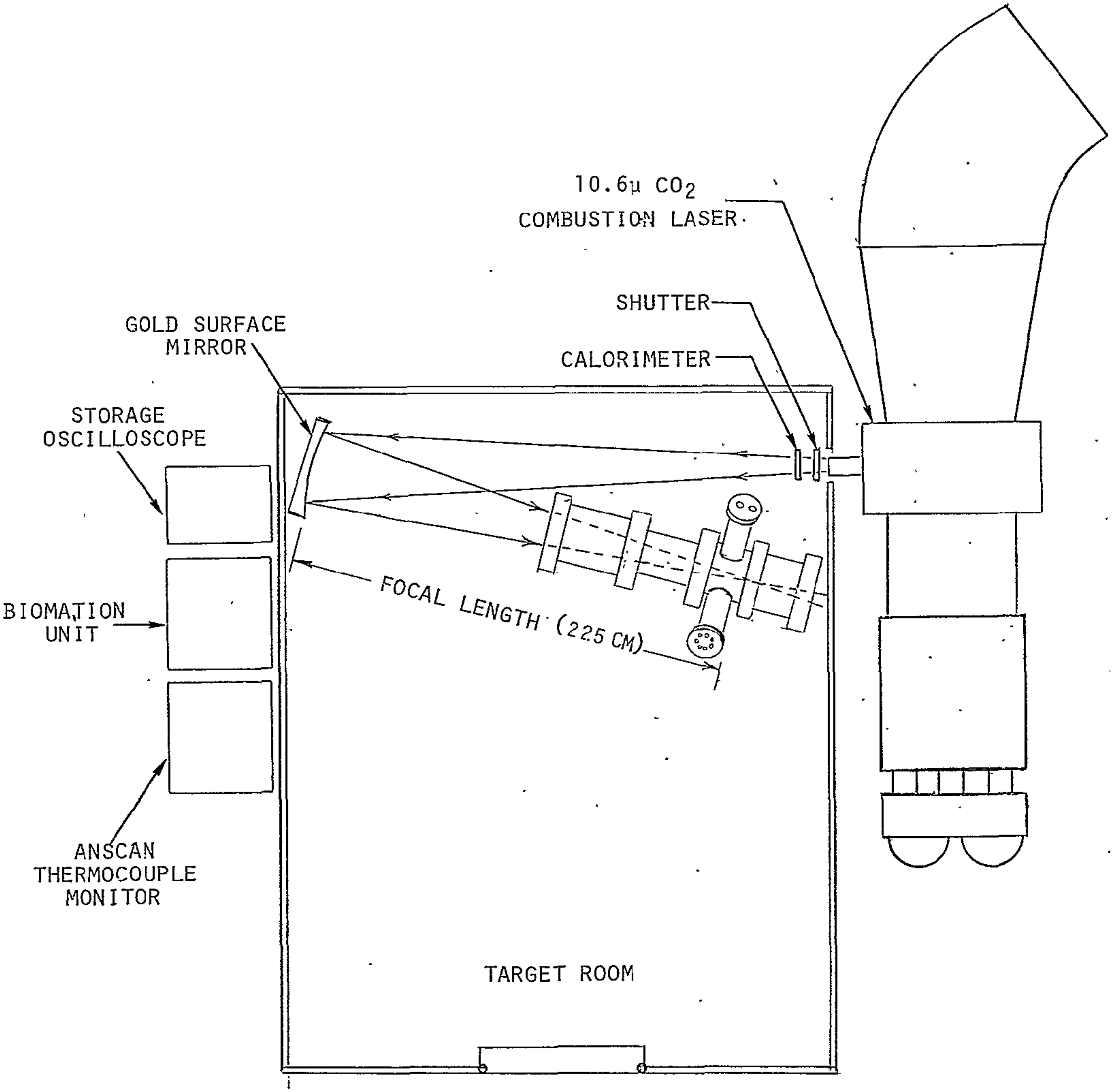


Fig. 8 TELEC Apparatus Installed in Optical Path of Ames Combustion Laser

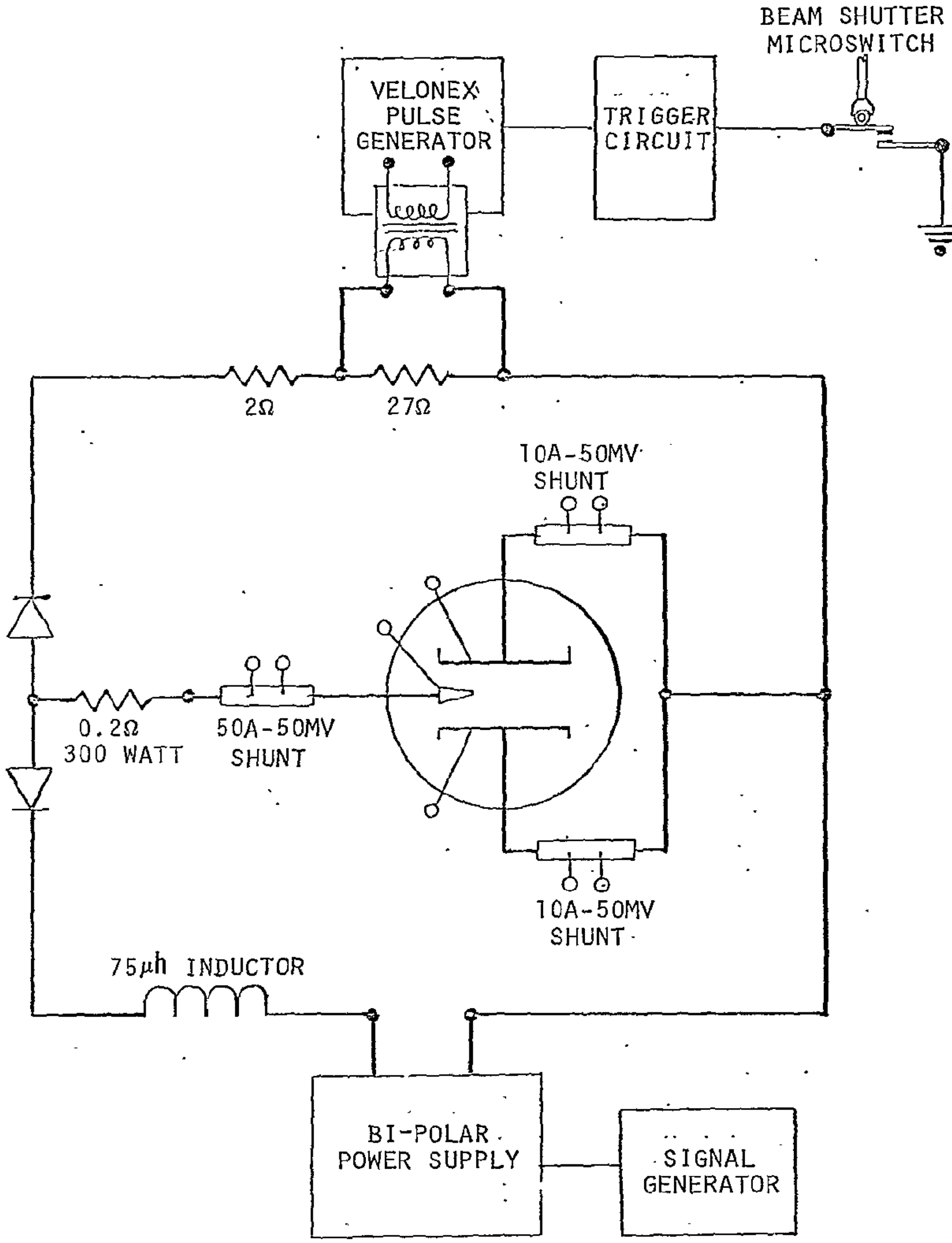


Fig. 9. Schematic Diagram of the Electrical Circuit Used TELEC Experiments

of the collector were monitored simultaneously and stored in a Biomation 4-channel digital waveform recorder, located outside the laser target room.

In addition to the 4-channel digital waveform recorder which obtains data for the TELEC current voltage characteristics, a storage oscilloscope is also used to monitor the current and voltage. This oscilloscope has high frequency response and can record rapid transients in the current or voltage and freeze the display on its display screen. After a trace has been stored on the oscilloscope screen, polaroid pictures are taken of the screen for a permanent record. A similar technique (polaroid camera) is also used to photograph the waveforms recorded on the Biomation digital waveform recorder.

4.2 Test Protocol

The laser facility has a pneumatically operated shutter and calorimeter system, which can measure the intensity of the laser beam and expose the apparatus to the beam for preset time intervals. The planned method for testing with the Ames laser was to initiate a plasma in the TELEC electrodes with a pulse from the Velonex pulse generator as the laser beam was admitted to the system. The voltage of the pulse generator can be adjusted from 0 to 300 volts and currents, up to 30 or 40 amperes can be delivered. The pulse generator is triggered by the beam shutter so the ionizing pulse occurs just as the beam exposure begins. This pulse produces a medium of ionized gas which can absorb the laser radiation, since the beam absorbtion is very small in a neutral gas of cesium.

A typical test begins when the cesium pressure has been established at the desired level and the TELEC test chamber. A trigger circuit which operates off the beam shutter microswitch is armed. This trigger circuit fires the pulse generator and also initiates the sweeps of the four channel digital waveform recorder and the storage oscilloscope. The voltage of the TELEC electrodes is continuously swept by an oscillating voltage source from the bipolar power supply during the entire test.

The laser power can be varied by nitrogen preheat before the laser shot. With cool nitrogen gas, low power exposure occurs (approximately 25 kilowatts), but as the nitrogen is preheated to its maximum temperature the beam power is increased to its highest power level (approximately 40-45 kilowatts).

On the first day of testing, the cesium was distilled into the system in the morning. Immediately a severe "frosting" of the inside salt windows was observed. When this reaction with the salt windows was seen, there was an urgency to get a shot through the system as quickly as possible in hopes of getting some data before the windows became completely opaque to the laser beam.

The first run was delayed for some time while the pulse generator was turned on to attempt to ionize the plasma without any laser beam present. This pretest was intended to show that a plasma could be produced prior to the laser exposure. There was concern that breakdown would not occur when the laser beam was admitted so some time was spent while the lack of ionization was investigated.

However no current was observed between the TELEC electrodes as the pulse generator was fired. The voltage of the pulse generator was increased up to its maximum level in a sequence of steps. It was found with the cold electrodes (no laser beam in the system) that even the maximum output of the Velonex pulse generator was unable to produce a breakdown in the cesium vapor. During these attempts to ionize the plasma with the pulse generator at its maximum voltage, some of the energy from the pulse generator damaged the recording instrumentation. Consequently, the first day's tests had to be carried out with incomplete data on the current and voltage measurements.

The reason for going ahead with the tests on that first day rather than repairing the recording instrumentation was to avoid the delay associated with the repair which would allow the windows to become even more opaque due to interaction with the cesium. The tests on the first day were carried out in the following manner because of the damaged instrumentation. The current in the emitter shunt was measured on the Biomation waveform recorder and the voltage between the emitter and one of the collector halves was recorded on the storage oscilloscope. The current measurements with the Biomation unit are somewhat doubtful on those first tests because of uncertainties as to the extent of the damage which may have occurred during the problem with the pulse generator. On the second and third days of testing the instrumentation was repaired, and the data was taken with proper information on the voltage and current characteristics of the TELEC cell.

Tests were carried out with the Ames laser on three days: June 2, 3 and June 8. A total of 10 runs were made with the laser beam during this time. The first nine runs were carried out with the salt windows intact, however on the 10th run the inner salt windows were deliberately broken by burning through them with the laser beam to bring the beam into the chamber at maximum intensity. The plasma was successfully initiated by the pulse generator in the presence of the laser beam although the previous attempts to do so without a beam had failed as mentioned before. In some of the runs the plasma initiated itself at a time which did not correspond with the occurrence of the ionizing pulse.

Surprisingly the beam could be transmitted through the frosted windows despite their opaque appearance to visible light. Apparently the products of the chemical reaction on the windows could either be temporarily removed by the sudden heating of the laser beam, or else the frosted windows are transparent to the 10.6 μ radiation. However the beam intensity in the TELEC chamber was considerably reduced after passing through the windows. Nevertheless it was verified that the beam passed clear through the system because burn patterns could be observed on an asbestos sheet behind the rear window. The amount of attenuation appeared to get successively worse as the testing went on through the three days.

4.3 Test Results

Run #1 - This was the first run with the laser beam in the system. The TELEC voltage was monitored on the storage oscilloscope, while the current in the emitter shunt was recorded on the Biomation waveform recorder. A 500 μs pulse of ~ 40 volts was used to initiate ionization in the plasma. Conditions of the run were as follows:

Time:	11:30 hrs. 2-June-1977
Laser Power:	25 kW
Run Duration:	~ 1/3 sec. (estimate)
Cesium Pressure:	~ 2 torr
Sweep Frequency:	~ 40 Hz

The current is shown in Fig. 10 and the voltage is shown in Fig. 11. Two complete voltage sweeps are seen in Fig. 11. The current trace is approximately constant at 6 amps except for some very brief negative transients. The lack of oscillation in the current trace suggests amplifier saturation or some similar instrument malfunction. Perhaps the current was actually larger than shown in Fig. 10. The voltage is almost entirely in negative region. However the voltage trace does appear to get very slightly above the zero line (~ 0.3 volts into the power producing region) so a small amount of output may have been generated.

There was considerable doubt that the laser beam could be transmitted through "frosted" salt windows. However this first run demonstrated that the beam passed through the entire TELEC chamber without damaging any of the windows. A burn pattern was obtained on an asbestos board placed behind the chamber which proved the beam was transmitted through the chamber. Furthermore, since a conducting plasma was formed and maintained, the beam was present inside the TELEC electrodes at a significant power level.

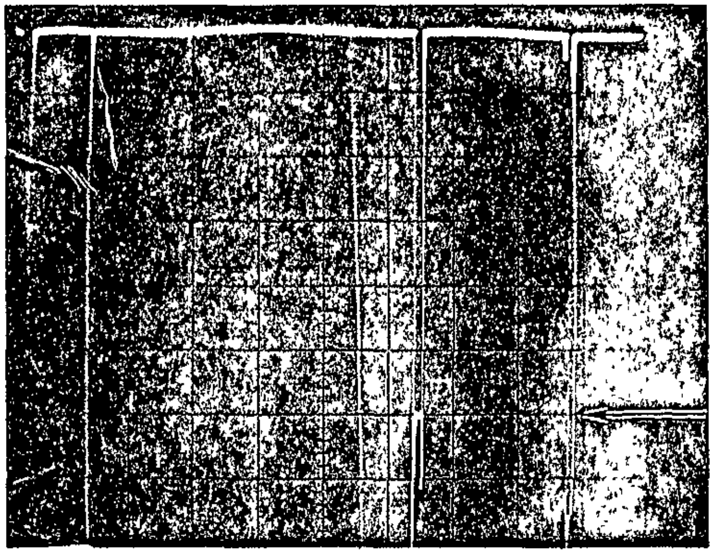


Fig. 10 Run #1 Current in the Emitter Shunt Recorded With Biomation Unit.

Vert. Scale: 1 amp/div

Hor. Scale: 5 ms/div

Zero level at 2 div. below center as indicated.

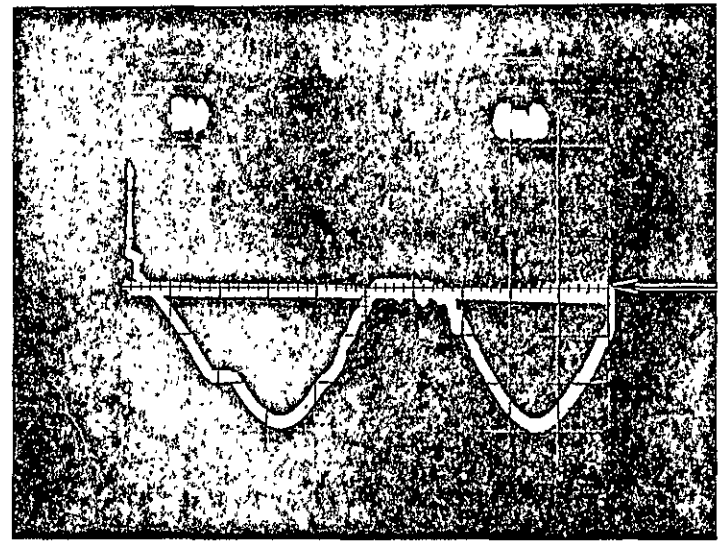


Fig. 11 Run #1 Voltage Between Emitter and Left Collector Measured on Storage Oscilloscope.

Vert. Scale: 2 volts/div.

Hor. Scale: 5 ms/div

Zero level in center of picture: Horizontal line is double exposure showing 0 volts.

Run #2 - This was essentially a repeat of the first run with the instrumentation set of different scales. The voltage and current were monitored on separate instruments as was done on Run #1. Conditions of the run were as follows:

Time:	12:00 hrs. 2-June-1977
Laser Power:	~ 30 kW
Run Duration:	~ 1/3 sec. (estimate)
Cesium Pressure:	~ 40 torr
Sweep Frequency:	~ 40 Hz

The TELEC current and voltage are shown separately in Figs. 12 and 13 respectively. Although the scale of the current trace is 10 times larger in this run, the current still shows approximately constant behavior with brief negative transients similar to the first run. Again, amplifier saturation may have occurred. Since the Biomation scale was 10 times larger, its amplifiers could not have saturated. However, saturation may have occurred in the differential preamplifiers whose scales were not changed on Run #2 from the value used on Run #1. The voltage trace in Fig. 13 has a smaller scale than Run #1 (0.5 volt/div. compared with 2 volt/div. on Run #1). The brief portion of the voltage trace which extends into the power quadrant can be more easily seen in this picture than in Fig. 12 from Run #1.

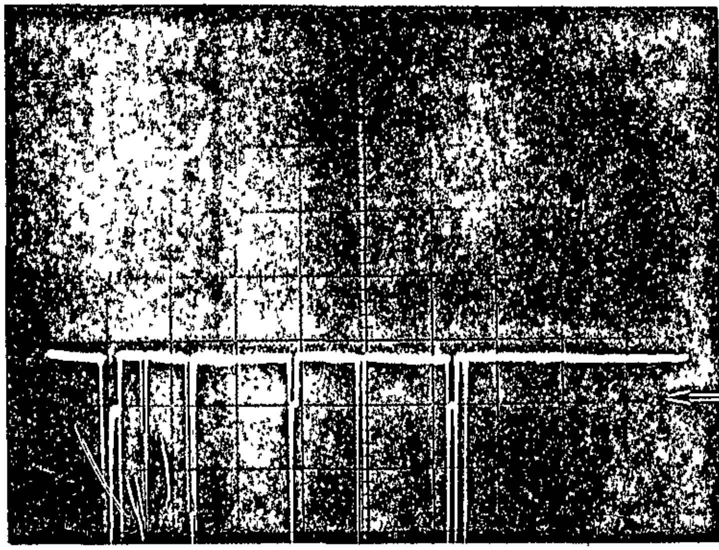


Fig. 12 <u>Run #2</u> Current in the Emitter Shunt Recorded with Biomation Unit.

Vert. Scale: 10 amp/div

Hor. Scale: 20 ms/div

Zero level at 2 division below center as indicated.

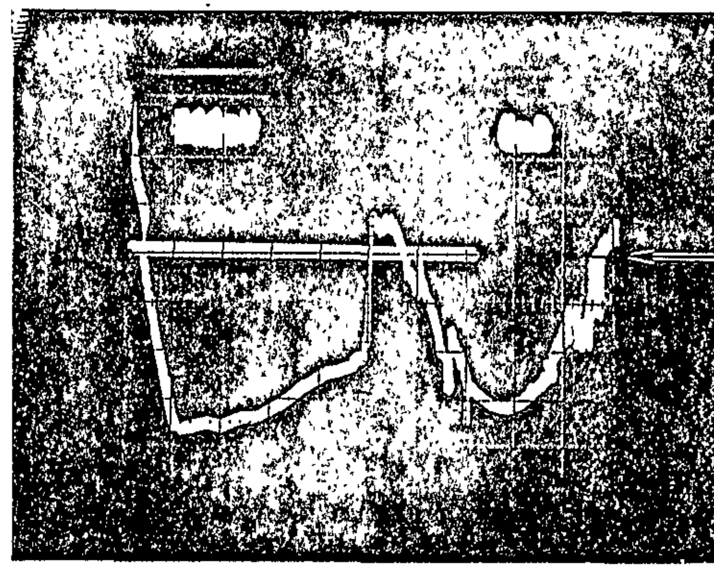


Fig. 13 <u>Run #2</u> Voltage Between the Emitter and Left Collector Measured on the Storage Oscilloscope.

Vert. Scale: 0.5 volts/div

Hor. Scale: 5 ms/div

Zero level at 1 division above center. Horizontal line is a double exposure showing 0 volts.

Run #3 - On the third run, the instrumentation and been partially repaired so that three channels of information could be stored in the Biomation digital waveform recorder. Although the Velonex pulse generator was connected for this run, it failed to trigger and did not fire a preionization pulse. The conditions of the run were as follows:

Time:	15:30 hrs. 2-June-1977
Laser Power:	~ 30 kW
Run Duration:	~ 1/3 sec (estimate)
Cesium Pressure:	~ 2 torr
Sweep Frequency:	~ 40 Hz.

The voltage and current for Run #3 are shown in Fig. 14. The voltage in the upper trace shows four negative-going sweeps of about - 6 volts amplitude. Both current traces remained constant at the zero level for the entire duration of the run.

The lack of current is due to the fact that the plasma was not ionized because the Velonex pulse generator failed to trigger on this run. Apparently, the laser beam intensity was not large enough to self initiate the plasma by beam absorption. Since the plasma was non-conducting, no current was observed.

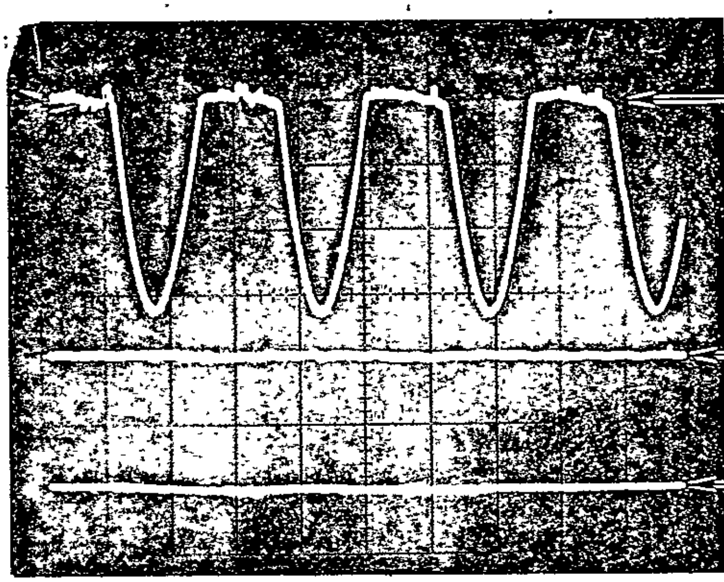


Fig. 14 Run #3 TELEC Voltage on Upper Trace. Emitter Current on Center Trace. Left Collector Current on Bottom Trace. All Traces Simultaneously Recorded on Biomation Unit.

Vert. Scales: 2 volts/div (Upper Trace)
2 amp/div (Center Trace)
2 amps/div (Bottom Trace)

Hor. Scale: 10 ms/div
Zero levels indicated on picture.

Run #4 - This was the first run of the second day. By this time the instrumentation had been fully repaired so that four channels could be simultaneously stored in the Biomation unit. The storage oscilloscope was also used as a backup and to show information at a different time rate. The sweep speed on the storage oscilloscope was set slower than the Biomation, so that the whole beam exposure could be monitored on the trace of the storage scope. The conditions of the fourth run were as follows:

Time:	11:30 hrs. [illegible]3-June-1977
Laser Power:	~ 30 kW (estimate)
Run Duration:	~ .4 sec.
Cesium Pressure	~ 4 torr
Sweep Frequency	~ 40 Hz.

The data traces recorded in the Biomation unit for Run #4 are shown in Fig. 15. The upper trace shows two sweeps of the TELEC voltage. The second trace shows a current in the emitter shunt and the bottom two traces show the currents in the left and right collectors respectively. Although an ionizing pulse was used prior to the first sweep, the traces in Fig. 15 indicate that a conducting plasma was not available until the second sweep, at which time currents are observed in all of the shunts. The voltage becomes erratic during the current conducting period. The current maximum occurs while the voltage is in the negative part of its sweep (out of the power quadrant). No power production was observed with record of Fig. 15.

Voltage and current measurements for Run #4 are shown at a slower sweep rate in Fig. 16 which was taken from the storage oscilloscope. There is a time period comprising ~ 20 complete voltage sweeps shown in this figure. The entire duration of laser beam exposure is included in the display. The current begins to flow on the second negative-going voltage sweep and continues for 11 sweeps. After the 11th sweep (period of approximately .35 second), the laser beam was turned off and the current flow stopped. The maximum value of the current observed in this run was approximately 6 amps as shown on the bottom trace. The current maxima all occur during the negative-going parts of the voltage sweep. No power output was observed on the storage scope display.

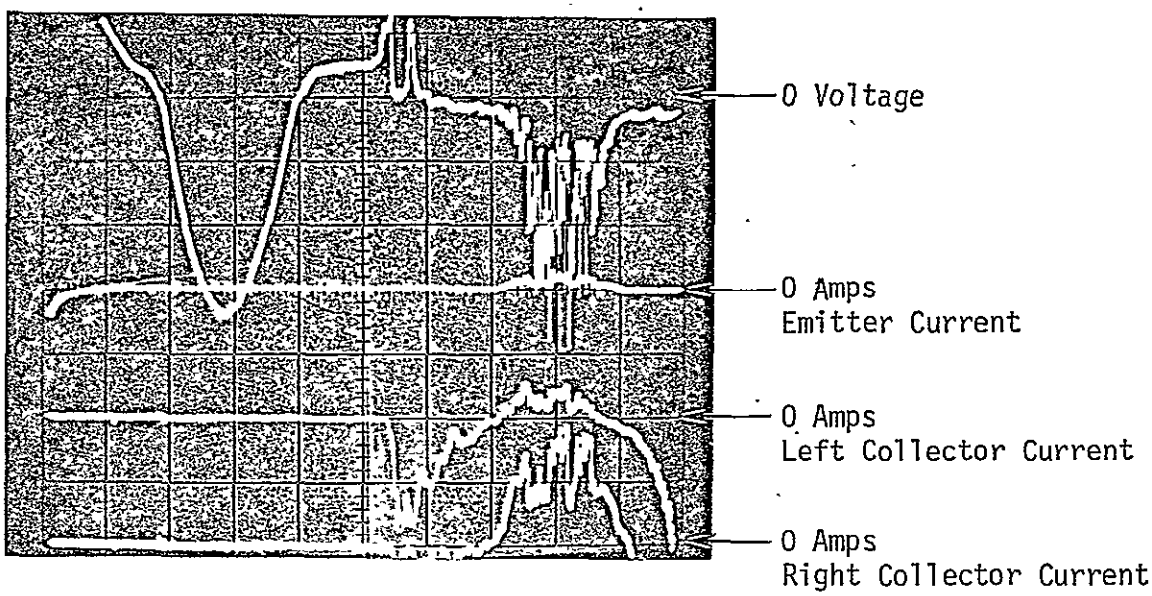
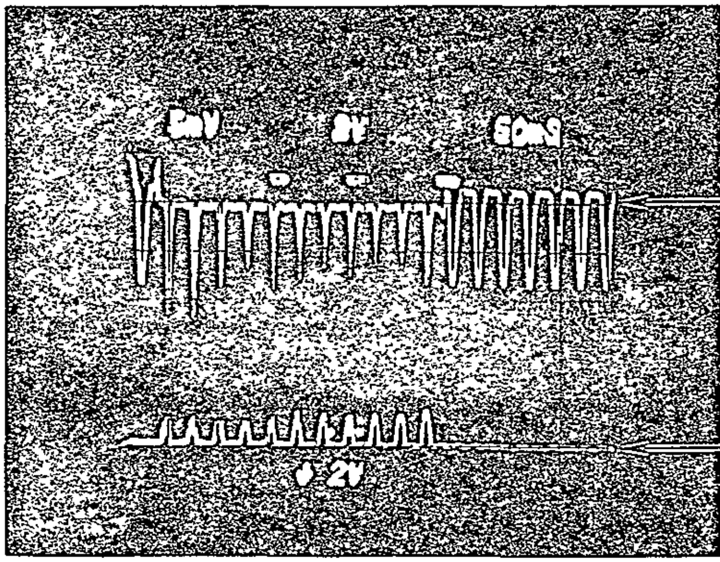


Fig. 15 <u>Run # 4</u> TELEC Voltage on Upper Trace. Current in Emitter Shunt on 2nd Trace. Current in Left Collector Shunt on 3rd Trace. Current in Right Collector Shunt on Bottom Trace.

Vert. Scales:	1 volt/div	(Upper Trace)
	10 amp/div	(2nd Trace)
	1 amp/div	(3rd Trace)
	1 amp/div	(Bottom Trace)

Hor. Scale: .5 ms/div

Zero levels indicated on picture.



-0 Voltage

-0 Amps
Emitter Current

Fig. 16 Run #4 TELEC Voltage on Upper Trace. Current in Emitter Shunt on Lower Trace.

Vert. Scales: 2 volt/div (Upper Trace)
5 amp/div (Lower Trace)

Hor. Scale: 50 ms/div

Zero levels indicated on picture.

Run #5 - The 5th run took place in the afternoon of the second day. Nitrogen gas used in the laser had been preheated for this run so the laser power was near its maximum value of approximately 45 kilowatts. This was the first high power run which was attempted. On previous runs the power level had been held down for protection of the windows, but their resistance to damage gave sufficient confidence to run at maximum power. The conditions of the run were as follows:

Time:	13:30 hrs. 3-June-1977
Laser Power:	~ 45 kW (estimate)
Run Duration:	0.6 sec.
Cesium Pressure:	~ 5 torr
Sweep Frequency:	~ 40 Hz.

Voltage and current data stored in the Biomation unit for the Run #5 are shown in Fig. 17. Four traces are shown in Fig. 17. The upper trace is the TELEC voltage with two complete sweeps visible. The second trace shows the current in the emitter shunt and the bottom two traces show the currents in the left and the right collector respectively. As shown in Fig. 17, the current does not begin to flow until the second voltage sweep, although an ionizing pulse was used at the beginning of the beam exposure. The delay in current conduction may be attributable to the time required for the emitter to become hot enough for thermionic emission. The current traces for the two collector halves in Fig. 17 each show a current of about 1/2 an amp on the second sweep. However, the emitter current (2nd trace) shows an almost negligible deflection because it was recorded on a scale of 10 amps/cm^2.

A longer time record is shown in Fig. 18, where the sweep speed was 50 ms/div. The emitter current trace at the bottom of Fig. 18 shows that the first two sweeps contained only a small amount of the current, but on the third sweep a current of approximately 1-1/2 amps begins and is present for 6 sweep cycles. However, on the seventh thru the 11th voltage sweep cycles the current increases to ~ 6 amps. The behavior of the voltage (upper trace) is particularly interesting during these four cycles. The waveform in these four cycles changes and goes positive up to a peak value of 0.6 to 0.7 volts. More importantly the peak current coincides with the peak in the positive-going voltage trace. This means the TELEC cell may have been producing power of approximately several watts during these four cycles. After these four cycles a current falls back and the voltage waveform reduces to a very small oscillation. The beam exposure is longer than the sweep time of the storage oscilloscope so the beam was still on at the end of the record shown in Fig. 18.

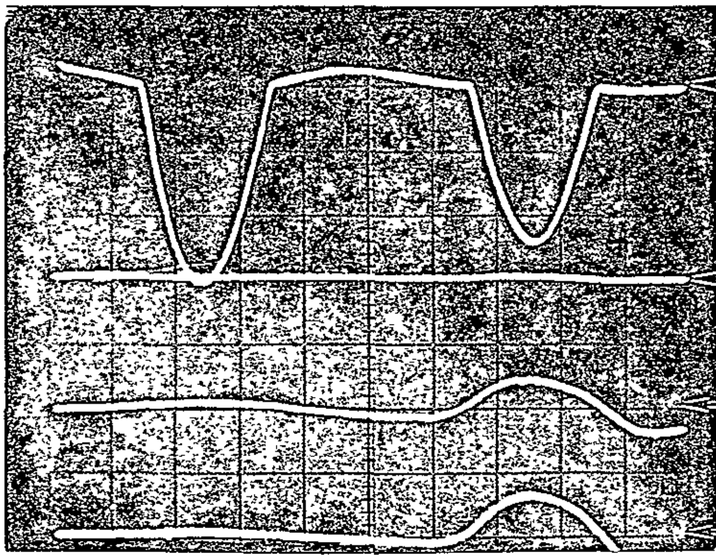


Fig. 17 Run # 5 TELEC Voltage on Upper Trace. Current in Emitter Shunt on 2nd Trace. Current in Left Collector Shunt on 3rd Trace. Current in Right Collector Shunt on Bottom Trace.

Vert. Scales:	1 volt/div	(Upper Trace)
	10 amp/div	(2nd Trace)
	1 amp/div	(3rd Trace)
	1 amp/div	(Bottom Trace)

Hor. Scale: 5 ms/div

Zero levels indicated on picture.

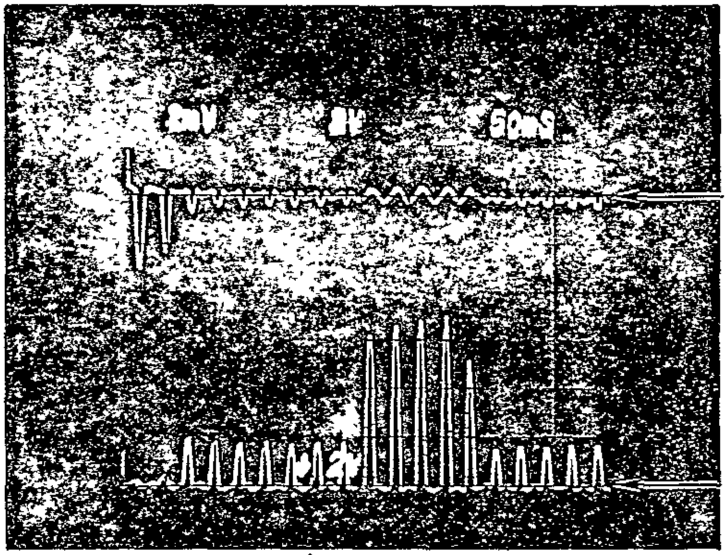


Fig. 18 Run #5 TELEC Voltage on Upper Trace. Current in Emitter Shunt on Lower Trace.

Vert. Scales: 2 volt/div (Upper Trace)
2 amp/div (Lower Trace)

Hor. Scale: 50 ms/div

Zero levels indicated on picture.

Run #6 - No sweep was used for this run. Instead the TELEC electrodes were connected across a resistive load for a steady-state operating point. An ionizing pulse was used to initiate the plasma. The conditions of Run #6 are as follows.

Time:	14:15 hrs, 3-June-1977
Laser Power:	45 kW (estimate)
Run Duration:	0.6 sec. (estimate)
Cesium Pressure:	~ 5 torr
Sweep Frequency:	0 Hz (DC operation)

Current traces for the two halves of the collector in the TELEC cell are shown in Fig. 19. The upper trace shows that the left collector current was negative for the duration of the beam exposure. The lower trace shows the current in the right collector shunt which was positive at a value of approximately 0.4 amps. Apparently the current flowed between the two halves of the collector instead of through the external load on this run. Negligible voltage and current was observed on the emitter during Run #6.

It is likely that beam scattering or slight misalignment caused the beam to impinge the left half of the collector and caused thermionic emission from that surface. This is supported by the opposite polarities of the currents seen in Fig. 19. The magnitude of the negative current is uncertain because the amplifier on the Biomation unit saturated in the reverse direction. The flat bottom of the current trace during the beam exposure is evidence of amplifier saturation. It is believed that if the amplifier had not saturated, the negative-going current signal from the left collector (upper trace) would be a mirror image of the positive current signal from the right half of the collector block.

Steady-state operation of the TELEC cell should have been possible with the apparatus which was tested. However, apparently the impedance choosen for the external circuit was too large, and beam misalignment prevented the plasma from being formed in contact with the emitter electrode.

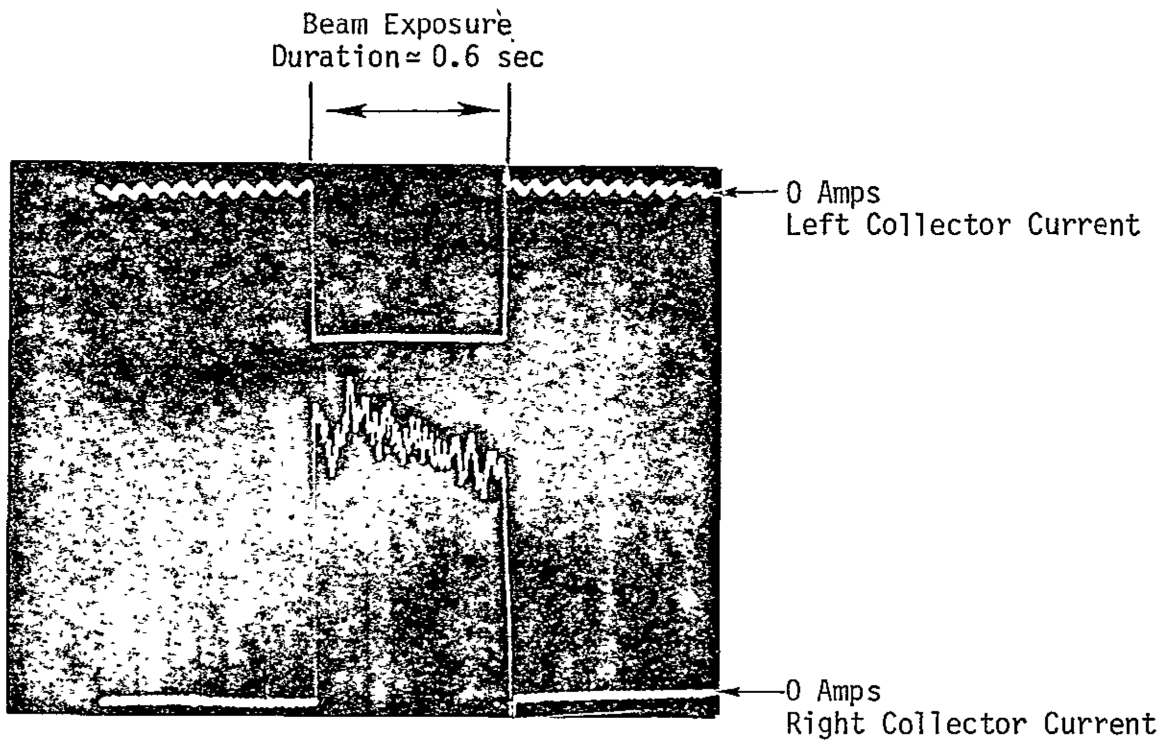


Fig. 19 Run # 6 . Steady State Currents in Left and Right Collectors of TELEC Cell With No Voltage Sweep. Left Collector Current is on Upper Trace. Right Collector Current is on Lower Trace.

Vert. Scales: 0.1 amp/div (both traces)

Hor. Scale: 0.2 sec/div

Zero levels indicated on the picture.

Run #7 - This was the last run of the second day. The laser beam run duration was increased to 1 second since the salt windows seemed to have no trouble withstanding the beam. The conditions of the run were as follows:

Time:	15:30 hrs. 3-June-1977
Laser Power:	45 kW (estimate)
Run Duration:	1 second
Cesium Pressure:	~ 5 torr
Sweep Frequency:	~ 40 Hz.

The current and voltage trace for the two halves of the collector are shown displayed in the I-V format in Fig. 20. The current is plotted on the vertical scale vs the voltage, which is displayed on the horizontal axis in these pictures. Many sweeps are shown overlaid resulting in the broad blurry character of the I-V trace. The current from the left collector is in the upper trace on the picture. Although the voltage in that trace does go into the positive region (to the right of the origin), the current is negative. On the lower display, both positive and negative current oscillations are shown. However these current excursions occur to the left of the origin (out of the power quadrant). No power was produced on this run.

The TELEC voltage and the current measured in the emitter shunt are shown in a time sweep in Fig. 21 which was taken from the storage oscilloscope. The current begins to flow after about the fourth sweep cycle and maintains an oscillatory waveform of about 3 amps throughout the rest of the trace. The current conduction always occurs when the voltage is in the negative part of its sweep and no power production is shown in this figure. It is not possible to display the information taken on the storage oscilloscope in the X-Y format to show I-V curves. Consequently, the time trace is all that can be shown. Direct comparision with the data from the Biomation unit is not possible in the X-Y format.

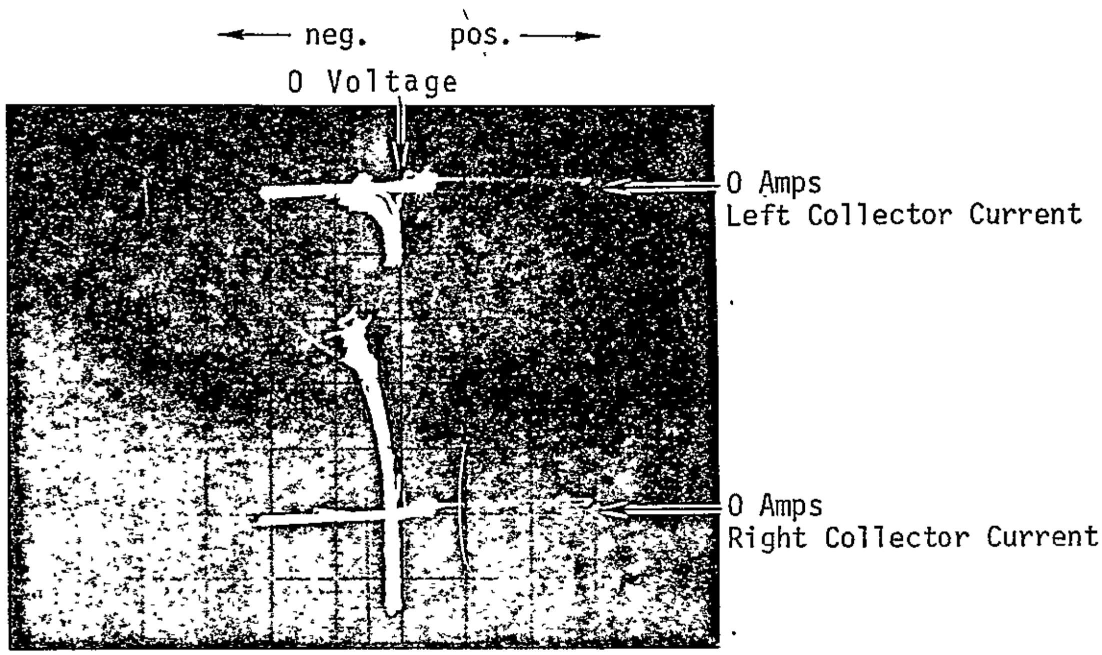


Fig. 20 Run #7 TELEC Current in Left Collector on Upper Trace. Current in Right Collector on Lower Trace. Both records were made with Biomation unit and are displayed here as current (vertical) plotted versus voltage (horizontal).

Vert. Scales: 1 amp/div. (both traces)

Hor. Scale: 1 volt/div

Vertical axis is 1 div. left of centerline as indicated. Horizontal axes for both traces are indicated on the picture.

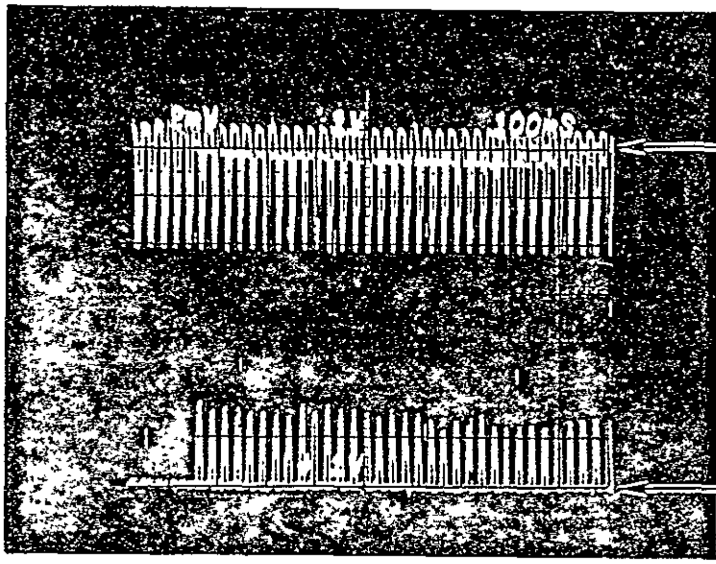


Fig. 21 Run #7 · TELEC Voltage on Upper Trace.
Current in Emitter Shunt on Lower Trace.

Vert. Scales: 1 volt/div (Upper Trace)
2 amps/div (Lower Trace)

Hor. Scale: 100 ms/div

Zero levels indicated on picture.

Run #8 - June 3 was a Friday and the system was left alone until the following Wednesday, June 8. Run #8 was the first run on that following Wednesday, June 8. The run took place in the afternoon and the nitrogen gas had been preheated so the laser was at maximum power. It was intended to test the TELEC apparatus up to the point of destruction during this sequence of runs. Conditions for Run #8 were as follows.

Time:	15:30 hrs. 8-June-1977
Laser Power:	~ 45 kW (estimate)
Run Duration:	1 sec.
Cesium Pressure:	~ 6 torr
Frequency:	~ 20 Hz.

One voltage trace and three current traces are shown as recorded in the Biomation unit in Fig. 22. The upper trace is the TELEC voltage. The 2nd trace is the emitter current and the bottom two traces are the left and right collector currents respectively. As shown in Fig. 22, no current develops in the emitter shunt until the 10th voltage sweep, although small currents are present in the split halves of the collector. On the tenth sweep, large oscillations begin to occur in the two collector current signals and a current is now visible on the emitter trace. The largest amount of current is present during the last few sweeps. However none of the current occurs while the voltage sweep is in the power quadrant.

A horizontally expanded view of the voltage and the trace and the emitter current is shown in Fig. 23. The last five sweeps are visible in the picture. The bottom trace shows a current in the emitter shunt of ~ 5 to 6 amps during some of the sweeps. Again, it is evident from this record that the current only occurs while the voltage is in the negative-going part of its cycle, and no power was produced on this run.

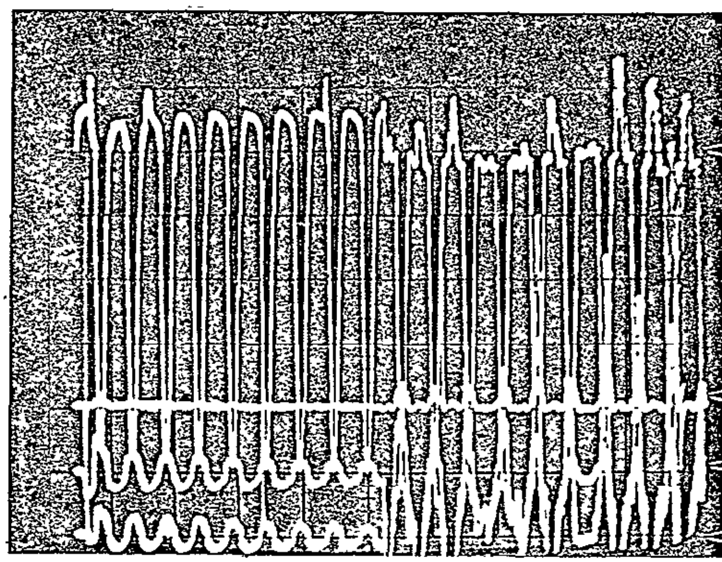


Fig. 22 Run #8 TELEC Voltage on Upper Trace. Current in Emitter Shunt on 2nd Trace. Current in Left Collector Shunt on 3rd Trace. Current in Right Collector Shunt on Bottom Trace.

Vert. Scales:	1 volt/div	(Upper Trace)
	5 amp/div	(2nd Trace)
	1 amp/div	(3rd Trace)
	1 amp/div	(Bottom Trace)
Hor. Scale:	0.1 sec/div	

Zero levels indicated on picture.

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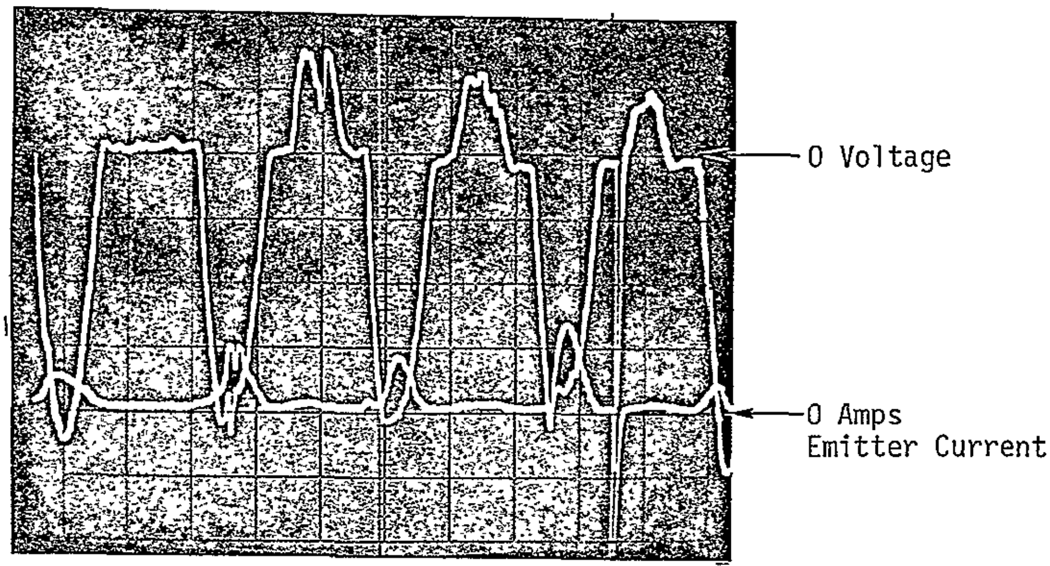


Fig. 23 Run #8 TELEC Voltage on Upper Trace. Current in Emitter Shunt on Lower Trace. Horizontal Magnification X5 of Biomation Record. Last 5 Voltage Sweep Cycles are Shown.

Vert. Scales:	1 volt/div	(Upper Trace)
	5 amp/div	(Lower Trace)
Hor. Scale:	20 ms/div	

Zero levels indicated on picture.

Run #9 - The ninth run was the last run made with the salt windows intact. The beam exposure duration was increased to 2 seconds and the laser was operated at full power ($\gtrsim$ 45 kW). By this time the salt windows had become very nearly opaque and it was felt that only a small part of the laser radiation was being transmitted into the TELEC chamber. It was hoped that during the long beam exposure time some cleaning of the windows by beam heating might occur, and allow a higher intensity to be transmitted during the last part of the run. The conditions for the 9th run were as follows.

Time:	14:00 8-June-1977
Laser Power:	~ 45 kW (estimate)
Run Duration:	2 sec.
Cesium Pressure:	~ 6 torr
Sweep Frequency:	20 Hz.

Traces of the TELEC voltage and the current in the emitter shunt as recorded on the storage oscilloscope are shown in Fig. 24. The current trace, which is at the bottom of Fig. 24, shows that the current flowed only for isolated brief periods on some of the sweeps. The current oscillations have larger amplitude and are more frequent at the last part of the run than at the beginning. The windows were so nearly opaque for this run that the plasma could not be continuously sustained by the beam. However the larger currents near the end of the run indicates that some cleaning of windows by the beam may have occurred.

An expanded view of some of the last voltage sweep cycles is shown in Fig. 25 which was recorded with the Biomation unit. The data in Fig. 25 contains four signals, the upper trace is the voltage, the second trace is the current in the emitter shunt, and the lower traces are the currents in the left and right collectors respectively. On one voltage sweep cycle (near the center of the picture) a large current of ~ 5 amps is conducted, yet no current flows in adjacent cycles on either side. The last sweep cycle shown in the picture has a large transient in the voltage which goes several volts into the positive direction. There is a small positive oscillation in the emitter current at this time also. Probably these current and voltage fluctuations are all due to an unsteady plasma which was being ignited and extinguished a number of times during the beam exposure.

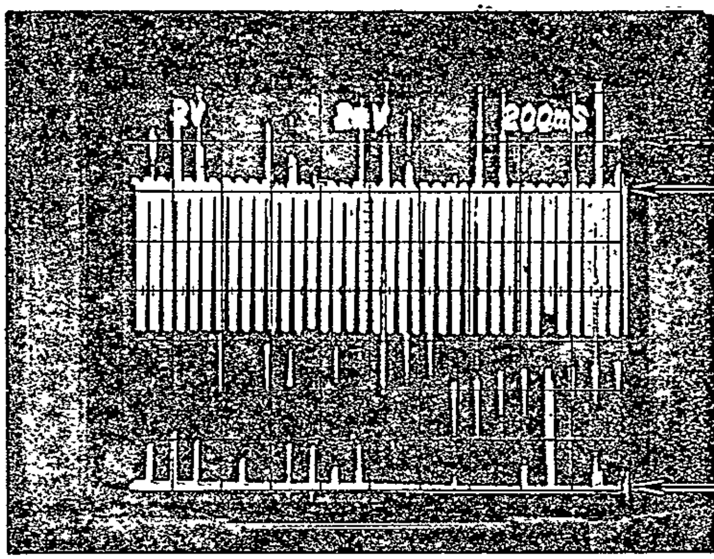


Fig. 24 Run #9 TELEC Voltage on Upper Trace. Current in Emitter Shunt on Lower Trace.

Vert. Scales: 2 volt/div (Upper Trace)
2 amp/div (Lower Trace)

Hor. Scale: 200 ms/div

Zero levels indicated on picture.

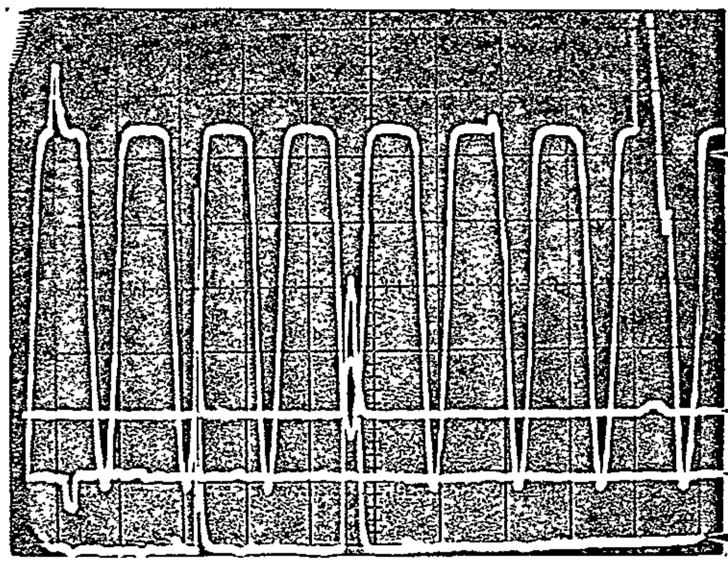


Fig. 25 <u>Run #9</u> TELEC Voltage on Upper Trace. Current in Emitter Shunt on 2nd Trace. Current in Left Collector Shunt on 3rd Trace. Current in Right Collector Shunt on Bottom Trace. Horizontal Magnification X5 of Biomation Record.

Vert. Scales:	1 volt/div	(Upper Trace)
	5 amp/div	(2nd Trace)
	1 amp/div	(3rd Trace)
	1 amp/div	(Bottom Trace)

Hor. Scale: 40 ms/div

Zero levels indicated on picture.

Run #10 - From the results of Run #9 it was clear that the degradation of the salt windows had become severe enough to reduce the beam intensity below the minimum value for plasma maintenance. On the 10th run it was decided to use maximum laser power for 4 seconds duration and deliberately burn-through the salt windows in order to expose the TELEC electrodes to the laser beam at full intensity. Since the frosted inner salt windows are exposed to a more concentrated portion of the laser beam, it was expected that these windows would be the first to fail. Consequently, cesium vapor would escape from the cesium part of the chamber into the vacuum regions between the windows on the ends. Of course the pressure during this time is uncertain and dynamically changing. At a later time when the larger outside salt windows would fail, air would be admitted into the chamber and all the cesium would be immediately oxidized.

However, during the time that cesium was escaping, data was obtained from the TELEC plasma until the cesium supply was exhausted. The sweep speed of both the storage oscilloscope and the Biomation unit were set to a slow rate (0.5 sec/div.). This allowed the entire 4-second run to be viewed on the scope display. The conditions of the 10th run were as follows.

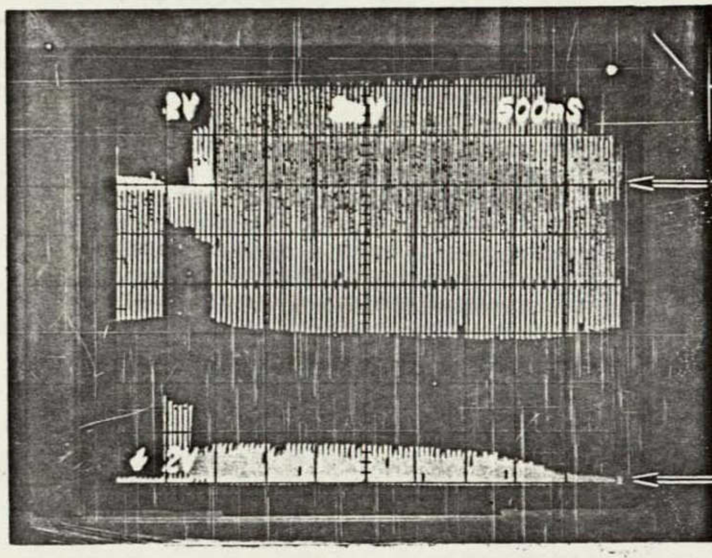
Time:	14:45 hrs. 8-June-1977
Laser Power:	45 kW (estimate)
Run Duration:	4 seconds
Cesium Pressure:	5 torr initial value (cesium escaped during the run)
Sweep Frequency:	20 Hz.

The TELEC voltage and the current in the emitter shunt are shown in Fig. 26. A delay of about half a second is observed at the beginning of the record in the figure while the laser beam was burning through the front inner salt window. During this time the voltage trace shows negative-going sweeps only and there is no current. After the half second delay, the beam enters the chamber and a current of about 3 amps begins to flow in the emitter shunt. The voltage still shows negative sweep traces only. This behavior persists for 6 sweep cycles and then the current falls to a lower value ($\lesssim$ 2 amps); but the voltage at this point begins to show positive as well as negative-going oscillations. The voltage sweep reaches a full amplitude positive and negative oscillation after about 1 full second, and maintains stable behavior of this type until the beam is turned off at the end of the four seconds. As the beam is shut down the voltage goes back to its negative sweep only, and the current shown in Fig. 26 decays to 0.

The time traces recorded in the Biomation unit during the 10th run are shown in Fig. 27. Four traces are shown in this figure. The upper trace is the T-ELEC voltage which is a duplicate record of the data in Fig. 26. The current in the emitter shunt and the second trace is also the same thing shown in Fig. 26. Additional data is contained in the bottom two traces, which show the currents measured in the left and right collector respectively. Examination of the collector currents shows that most of the currents is conducted by the left collector. Only a small amount of current flowed through the right collector shunt.

Volt-ampere curves for each of the three currents measured in Run #10 are shown in Fig. 28. The upper trace shows an I-V curve for the emitter shunt which represents the total current in the cell. This trace gets out into the power quadrant to about 3 volts with a current of somewhat less than 1 ampere. However the shape of the volt-ampere curve is unusual and unlike what is expected from the calculational predictions. Normally the current should decrease as the voltage increases. However, the curves shown in Fig. 28 have increasing currents as the voltage goes out further into the positive power quadrant.

The data recorded in the Biomation unit was expanded in time and examined cycle by cycle for detailed comparison of the currents in each of the electrodes at each point in time. It was expected that the total algebraic sum of all the currents measured in the 3 shunts would equal 0, as required by current continuity. However the detailed examination of the expanded record revealed that, on this particular run, the sum of the currents measured in the collector shunts does not equal that which enters in the emitter shunt. Consequently, it is believed that a conducting path in the plasma to the metal chamber was formed during the run. Some of the current must have flowed through this plasma path to the grounded chamber and thus could have given an incorrect reading.



0 Voltage

0 Amps
Emitter Current

Fig. 26 Run #10 TELEC Voltage on Upper Trace. Current in Emitter Shunt on Lower Trace.

Vert. Scales: 2 volt/div (Upper Trace)
2 amp/div (Lower Trace)

Hor. Scale: 0.5 sec/div

Zero levels indicated on picture.

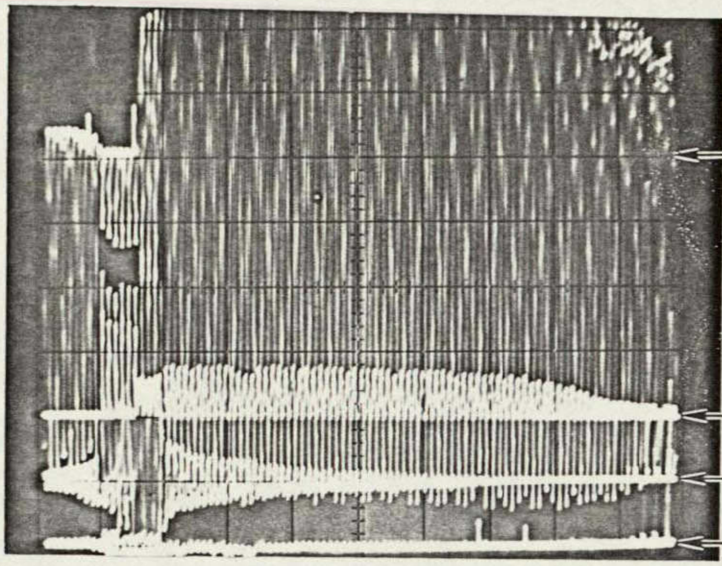


Fig. 27 Run #10 TELEC Voltage on Upper Trace. Current in Emitter Shunt on 2nd Trace. Current in Left Collector Shunt on 3rd Trace. Current in Right Collector Shunt on Bottom Trace.

Vert. Scales: 1 volt/div (Upper Trace)
2 amp/div (2nd Trace)
1 amp/div (3rd Trace)
1 amp/div (Bottom Trace)

Hor. Scale: 0.5 sec/div

Zero levels indicated on picture.

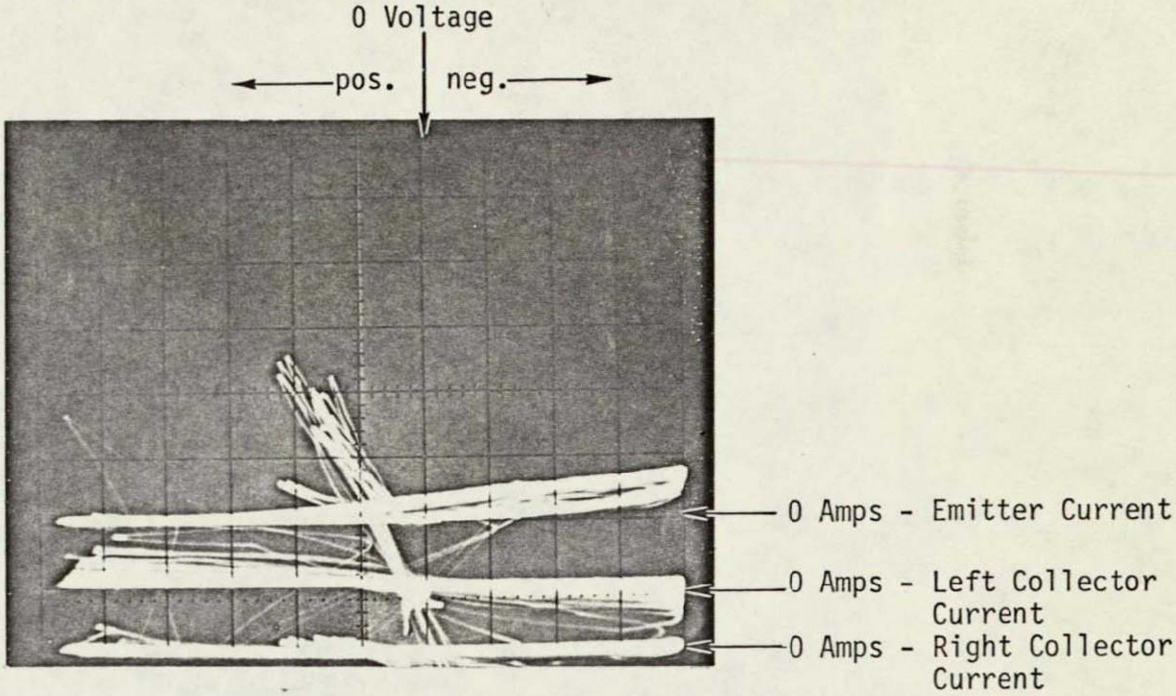


Fig. 28 Run #10 Volt-Ampere Curves for the Emitter Shunt (Upper Trace) and the Left and Right Collectors (2nd and Bottom Traces Respectively). Current (Vertical) is Plotted Versus Voltage (Horizontal).

Vert. Scales: 2 amp/div (Upper Trace)
1 amp/div (2nd & Bottom Traces)

Hor. Scale: 1 volt/div

Vertical axis is 1 div. left of centerline as indicated. Horizontal axes for all three traces are indicated on the picture.

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5.0 DISCUSSION OF THE RESULTS

5.1 Comparison With Theoretical Calculations

A plasma model for TELEC behavior, which has been analyzed theoretically, was used to calculate the expected performance of the experimental TELEC cell. These calculations predict that a minimum laser beam intensity of $\gtrsim 10$ kW/cm^2 is required to sustain a plasma and produce TELEC output power. Since the beam diameter in this experiment was ~ 1 cm, scattering or attenuation through the frosted windows could easily reduce beam intensity from ~ 40 kW to near the threshold for plasma maintenance. Thus any TELEC output obtained with the frosted windows would likely be small.

One area of concern in interpreting the experimental results is to avoid confusing low level TELEC output with possible thermionic converter behavior. If beam impingement on the emitter raises its temperature sufficiently high (~ 1800° to 2000°K) the TELEC cell could produce power as a thermionic converter. However, calculations based on the theoretical model predict that a TELEC cell can produce a higher voltage than a thermionic converter, so the two types of behavior should be distinguishable. The calculated performance for the experimental TELEC cell operating in cesium at ~ 2 torr with a laser beam input of 40 kW predicts a current of several amps at about 3 volts. This is a larger voltage than can be produced with a thermionic converter, which has a voltage of ≤ 1 volt. The calculated TELEC output voltage is only greater than a thermionic voltage for high laser powers. If the beam intensity is reduced by poor window transmission, the TELEC output voltage is expected to be no larger than thermionic voltage.

On Run #10 the windows were broken by the beam to get full intensity laser power in the cell so the output of that run might be comparable with analytically predicted performance. The predicted current of several amps at ~ 3 volts is in relatively good agreement with the end point of the I-V curve shown in Fig. 28. However, as mentioned before, the shape of a calculated TELEC volt-ampere characteristic is different from the observed trace in Fig. 28. A comparison of the calculated and experimental results can be seen in Fig. 29 where a calculated operating point and a theoretical I-V curve have been superimposed on the oscilloscope photograph from Run #10. The anomalous shape of experimental I-V curve may have been due to plasma short circuiting some of the current to the chamber walls. This possibility was investigated further as described below.

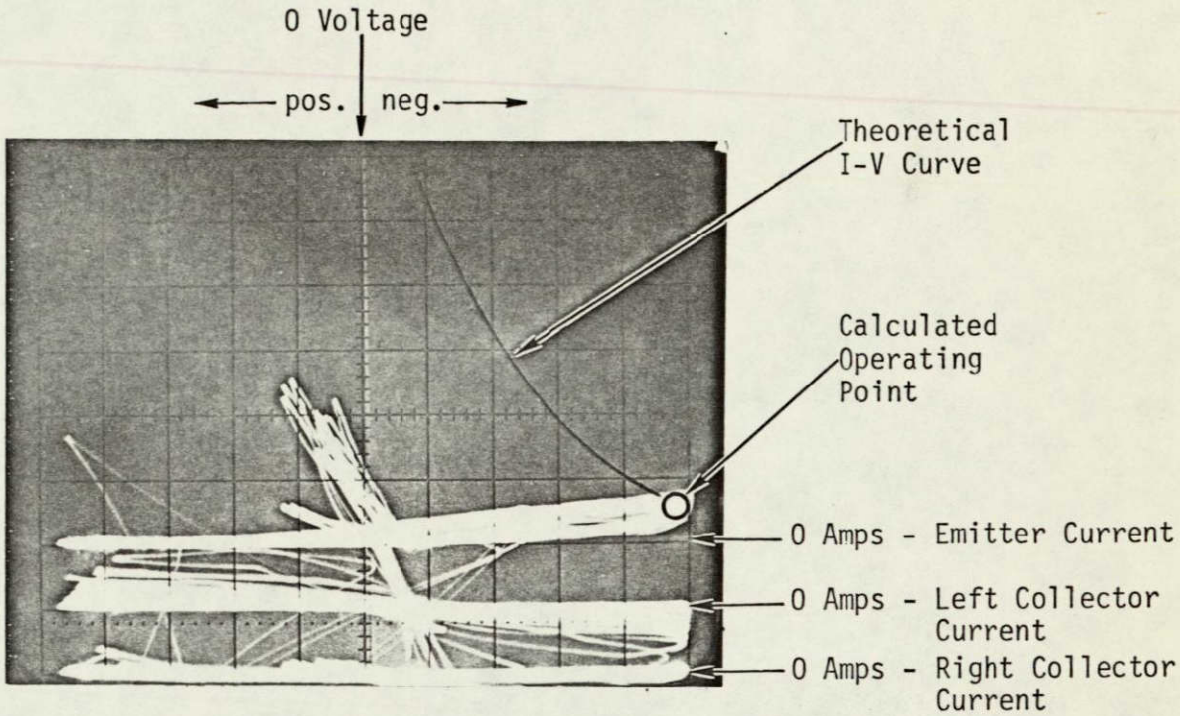

Fig. 29 TELEC I-V Curve Compared With Performance Predicted by Theoretical Calculations.

is to use a chamber which acts as a cesium heat pipe with an inert gas buffer at the ends to confine the cesium vapor to central region and keep it away from windows on the ends. A system of the type is presently under construction.

Small amounts of putput power from TELEC operation were tentatively observed on several of the experimental runs. The 7th through 11th sweep cycles in Run #5 are of interest in this light. The voltage during these 4 sweeps was in power quadrant while currents of ~ 6 amps flowed. However the data for that part of Run #5 were recorded on only the storage oscilloscope and thus it is not possible to observe the shape of the I-V curves. Any output voltages were less than 1 volt and this does not preclude thermionic converter effects. Yet this low voltage is reasonable for TELEC output with low beam intensity caused by poor transmission through frosted windows.

On the 6th run, some small power was produced as DC current flowed through the parallel shunts from one half of the collector to the other half. Again this is a very small amount of output and it consists only of current through an approximate short circuit. However, because the temperature of the collector halves were monitored during the run, it is known that collector temperature did not rise high enough to produce thermionic converter output. Thus the small current which flowed between collector halves was due to TELEC behavior.

The performance of the 10th run obtained a voltage greater than would be possible from a thermionic converter effect. However, this result is doubtful because the plasma apparently conducted some current to the metal chamber and may have distorted the I-V curves for that run. In future experimentation, this problem could be prevented by using cesium chamber which is ungrounded.

The overall conclusion is that TELEC plasma operation is possible but an unambiguous demonstration of TELEC practical feasibility will require further experimentation with a different type of window system.