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*University of California/Livermore, California*

# EXPERIMENTAL RESULTS ON THE TWO-STAGE, VENETIAN BLIND, DIRECT ENERGY CONVERTER

R.W. Moir
W.L. Barr

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## ABSTRACT

This report describes some preliminary results obtained from experiments designed to test the feasibility of the Venetian Blind, direct energy-conversion concept. A two-stage unit was built and tested and found to have an overall efficiency of 65% for an energy spread of from 330 to 1000 eV. The calculated efficiency was 69% leaving a 4% discrepancy. This discrepancy seems to result from the slight transparency in the backward direction of the ribbons of the converter.


## INTRODUCTION

The Venetian Blind direct energy converter takes its name from the use of ribbon-like equipotential surfaces which are more transparent to ions going forward than to ions going backward. The angular dependance of transmission through such a system gives the ions a parabolic trajectory.

The converter is designed so that the electric field is uniform and directed at a small angle ($\alpha_0$) from exact opposition to the initial ion beam. An ion entering this system will pass through surfaces of successively increasing potential until it turns and starts back. It then sees rather opaque surfaces and will be caught. In this way ions are sorted according to energy, with high-energy ions being caught on high-potential electrodes. Figure 1 shows a two-stage, direct converter where, as always, the last stage is completely opaque.

The use of one, two, three, and four stage versions of the Venetian Blind concept on toroidal and mirror fusion reactors has been discussed.[1] An economic and engineering study[2] of the feasibility of adapting the concept to the mirror fusion reactor has also been made. Some of the results reported here were presented at the recent APS meeting.[3]

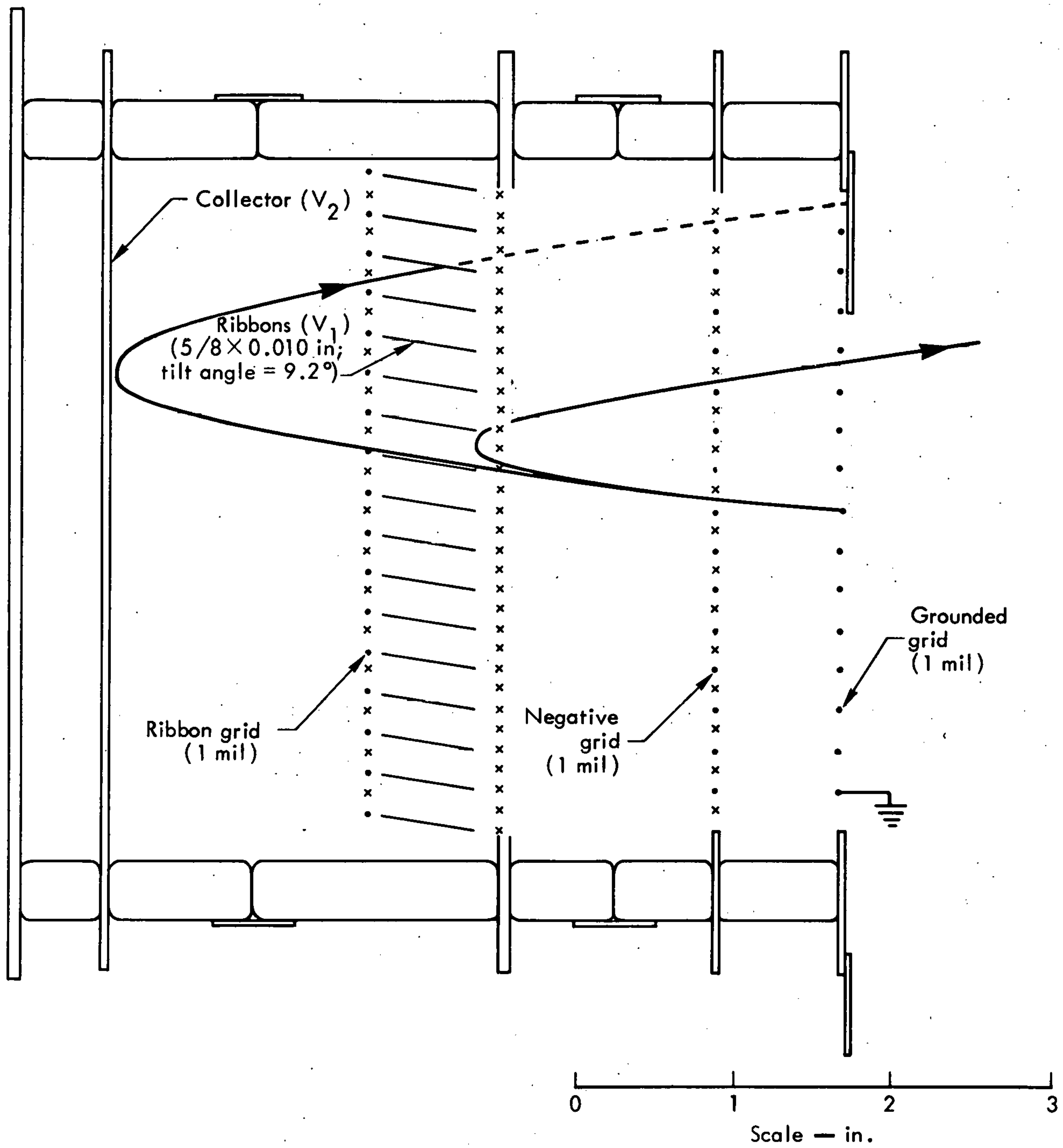


Fig. 1. Cross section of 2-stage, Venetian Blind, direct converter with typical ion trajectories.

## RESULTS

### Fixed Ion-Beam Energy

To test out our idea, we scaled down our design[3] for a two-stage, Venetian Blind, direct energy converter by a factor of 12 (see Figs. 1 and 2). The converter was located at the end of the magnetic expander of the direct conversion test facility (see Ref. 4 and Fig. 3). A hydrogen ion beam was directed down the magnetic expander towards the collecting structures.

In order to simplify the initial experiments we operated at constant current. The ion beam energy was left unchanged and the converter potentials were varied to simulate the variation of beam energy. The voltage on the collector (plate), $V_2$, was varied from 200 to 600 V. The voltage on the ribbons, $V_1$, was held at half the voltage of the second collector. The ribbon grid was held at 0.89 times the voltage of the ribbons to suppress secondary electrons.

In order to compute an efficiency it was first necessary to convert the energy of the constant current source to the corresponding value for an ion source of variable energy. This equivalent energy, $W'$, was defined by

$$W' = \frac{200{,}000/\cos^2 \alpha_0}{V_2} ,$$

for a 300-eV, fixed-beam energy. The efficiency is

$$\eta(W') = \frac{I_1V_1 + I_2V_2 + I_{neg.grid}V_{neg.grid} + I_{rib.grid}V_{rib.grid}}{IV_{beam}},$$

where I is the total incident current including that lost on the grounded grid. The efficiency calculated from this type of measurement is shown in Fig. 4. It can be seen that while the efficiency of the collector was quite good, the ribbons were apparently lossy. One source of this loss was thought to be due to the fringe field or nonparallel equipotential near the grids. As the ion passes the several grids and ribbons the trajectory

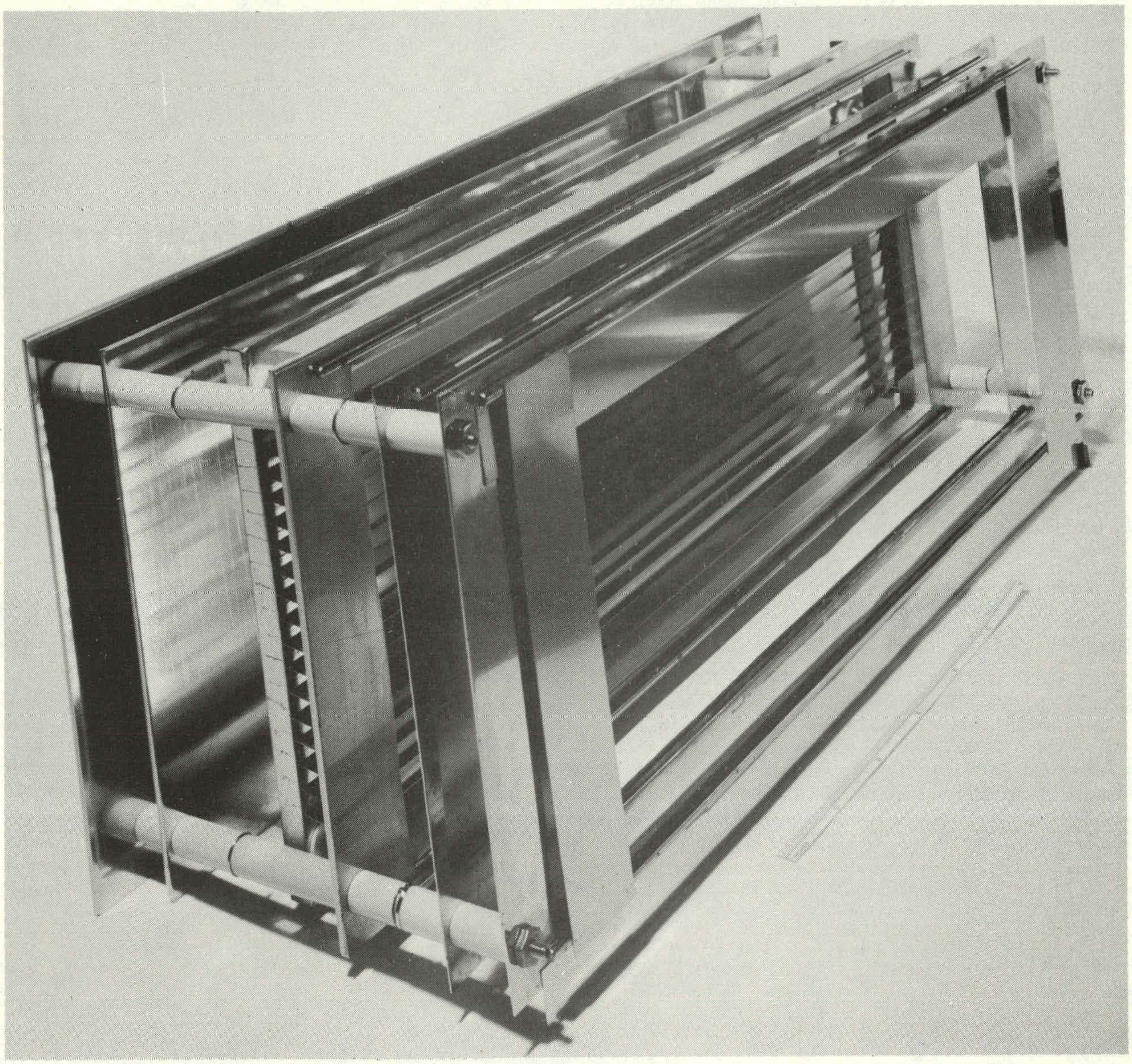

Fig. 2. The 2-stage, Venetian Blind collector.

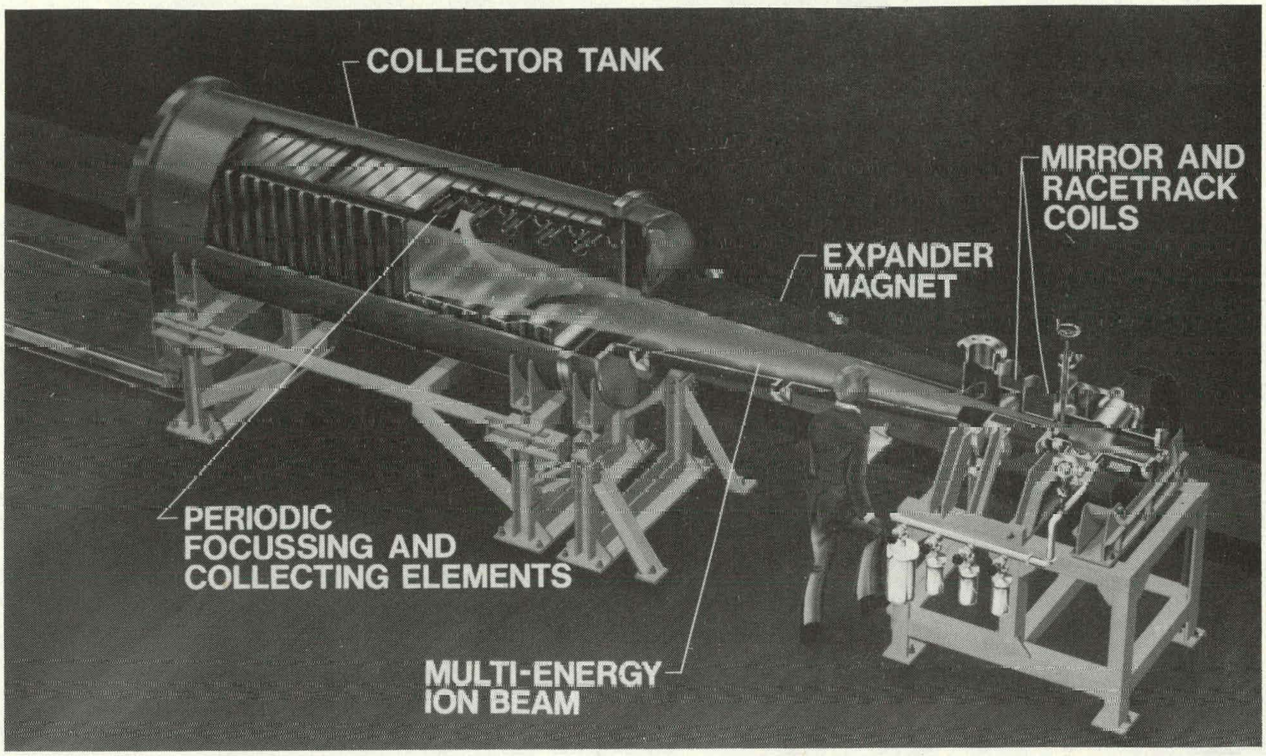


Fig. 3. Direct energy conversion test facility.

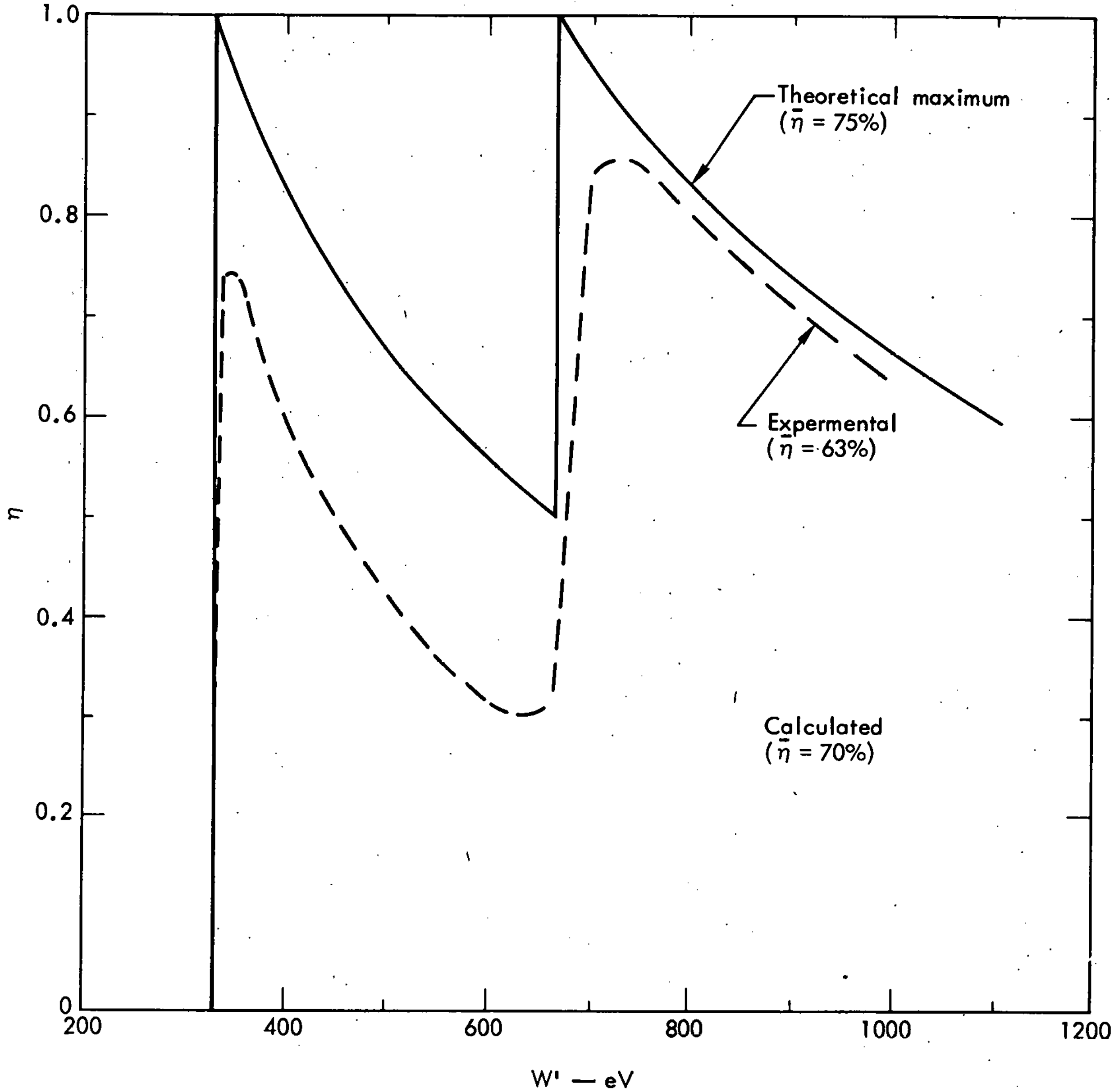


Fig. 4. Experimental and ideal efficiency versus equivalent energy for the 2-stage collector.

can be altered from a simple parabola if the equipotential surfaces are not planar. This will introduce angular dispersion in the beam giving the same result as varying the entrance angle, and any angle less than 6.9° should lead to current loss.

To test this, we added 0.001-in. tungsten grid wires at 0.125-in. spacing (denoted by x marks in Fig. 1). We expected these wires to smooth out the field and make the equipotentials more nearly parallel. Unfortunately, at the same time we also added a more restrictive collimator and extended the grid frames to reduce edge effects. Although we do not know precisely how important these extra grids were, qualitatively they seemed unimportant. All the results except those shown in Fig. 4 were obtained with the extra grids.

The current collected on the converter with these extra grids is shown in Fig. 5. Also shown are the calculated values of collected currents. These calculations assume that the ribbons are thin and that the entrance angle of the beam has no spread. The measured currents are roughly the same as those predicted, except for the lower current measured at 300 to 600 V. This will be discussed more in the section on variable energy.

Efficiencies were calculated from the measured results shown in Fig. 5. These experimentally determined efficiencies are plotted and compared with plots of the practical calculated efficiency and the maximum theoretical efficiency in Fig. 6. Average efficiencies from 333 to 1000 eV are also shown in this figure. The calculated average efficiency was 69% and the experimental result was 65%. The 4% difference is discussed in the next section.

## Variable-Energy Ion Source

We also performed experiments in which we varied the ion energy and kept the collector voltage, $V_2$, fixed at 600 V; however, one run was at 667 V. The ribbon collector was kept at half the collector voltage. The tilt angle of the converter with respect to the beam ($\alpha_0$) was 3.9°, 6.9°,

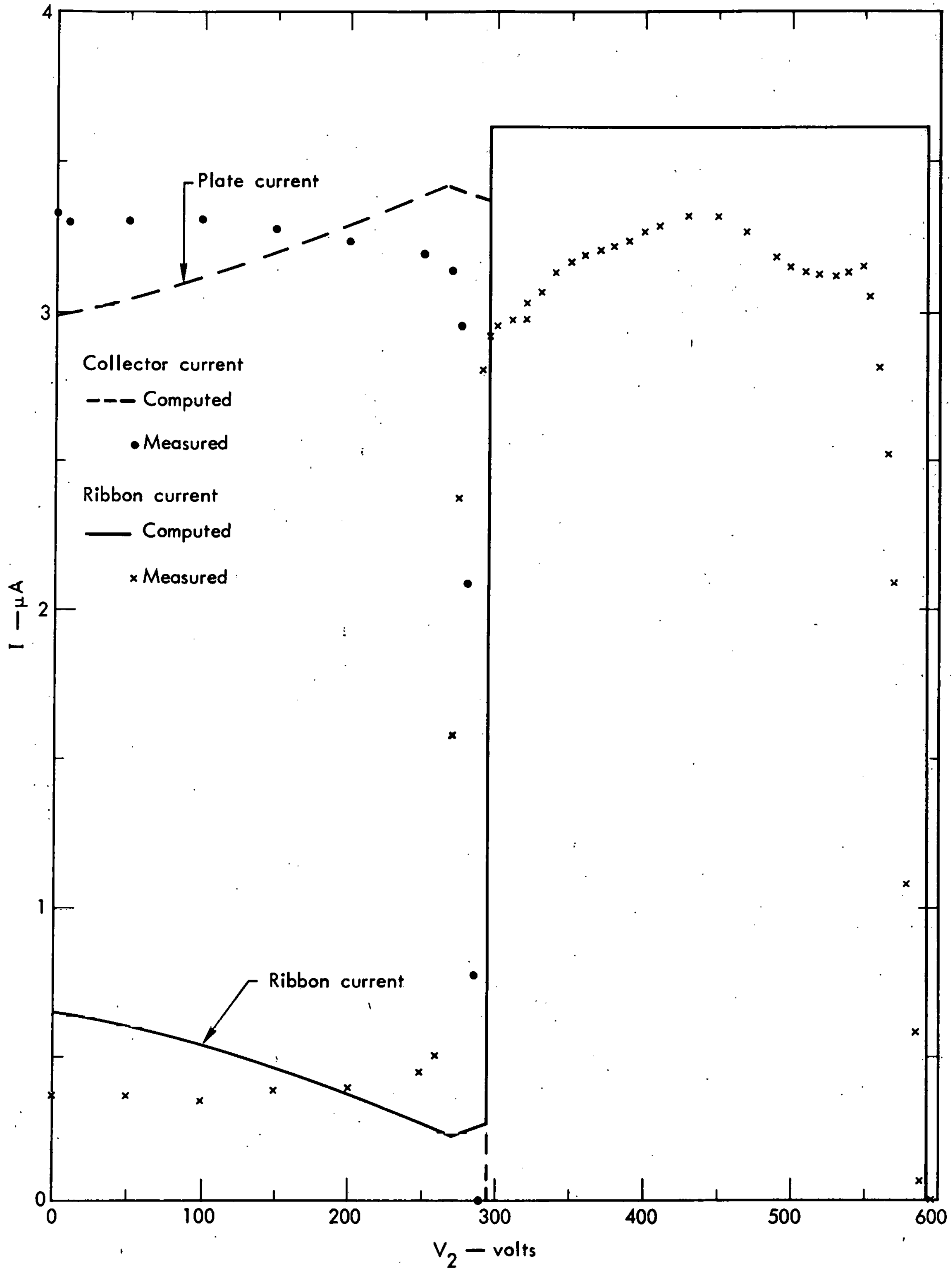


Fig. 5. Measured and calculated current versus voltage on the collector for the increased number of grids.

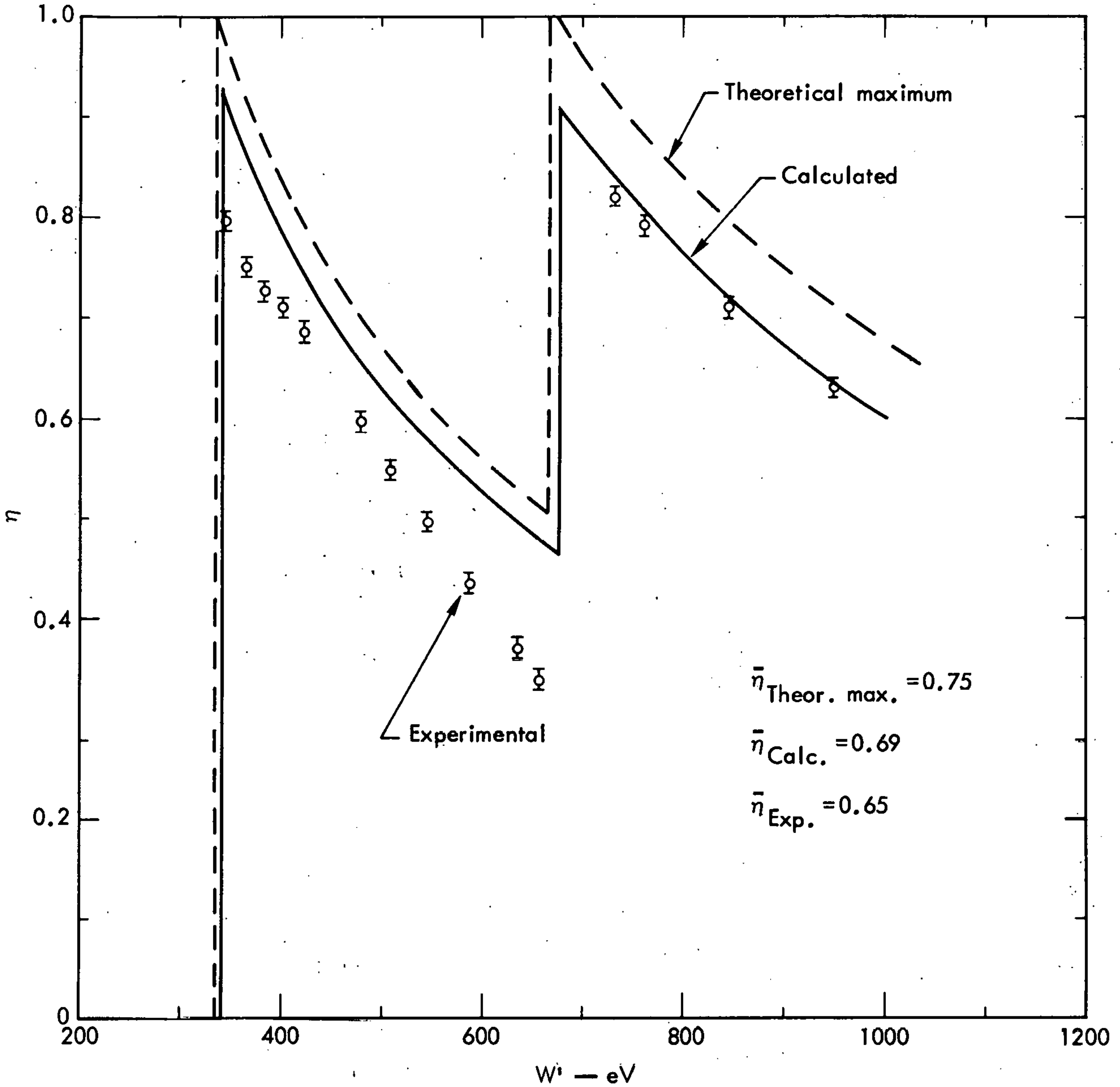


Fig. 6. Experimental, calculated, and maximum efficiency versus equivalent energy.

and 9.9° in separate runs. Because of the low voltage range of the particular power supply we used, the beam energy ranged only up to 700 eV for most of this data. Raw data showing the collected current versus beam energy is presented in Figs. 7-9. The computed efficiencies are shown in Figs. 10-12. The efficiency is calculated from the formula

$$\eta = \frac{I_{ribbon}V_{ribbon} + I_{coll}V_{coll} + I_{neg.grid}V_{neg.\ grid} + I_{rib.grid}V_{rib.grid}}{IV_{accel}}$$

where I is the total current and is measured with all collectors at zero volts.

One clearly noticeable fact is that all the current is not accounted for. That is, the current collected on the ribbons, ribbon grid, collector, and negative grid does not add up to the current injected. We speculate that this is due to the ribbons not being completely opaque to returning ions. When the tilt angle was 3.9° (less than the design optimum of 6.9°) the quantity of missing current was large. At 9.9° it was smaller, but still significant. The spread in the entrance angle should be quite small, perhaps as low as ±2°. We speculate that there are two explanations for this current loss and the related 4% loss in efficiency cited earlier.

The first possibility is that irregularities in ribbon spacings and angles result in gaps and allow some ions to escape. We intend to increase the opacity of the collector by widening the ribbons from 5/8 in. to perhaps 1 in. in the next experiments.

The second explanation of the missing current has already been mentioned in connection with the fixed beam experiments and has to do with the fringe fields around the ribbons and grids. The effect of fringe fields seems to be difficult to study experimentally, but should be amenable to analysis. We can study this effect by numerical trajectory calculations with the DART code[5] using two-zone potential solving technique[6] for handling abrupt changes around grid wires and the edges of ribbons.

Another result we see in Figs. 10, 11, and 12 is that the efficiency does not rise straight up as calculated at $300/\cos^2\alpha_0$ and $600/\cos^2\alpha_0$, but

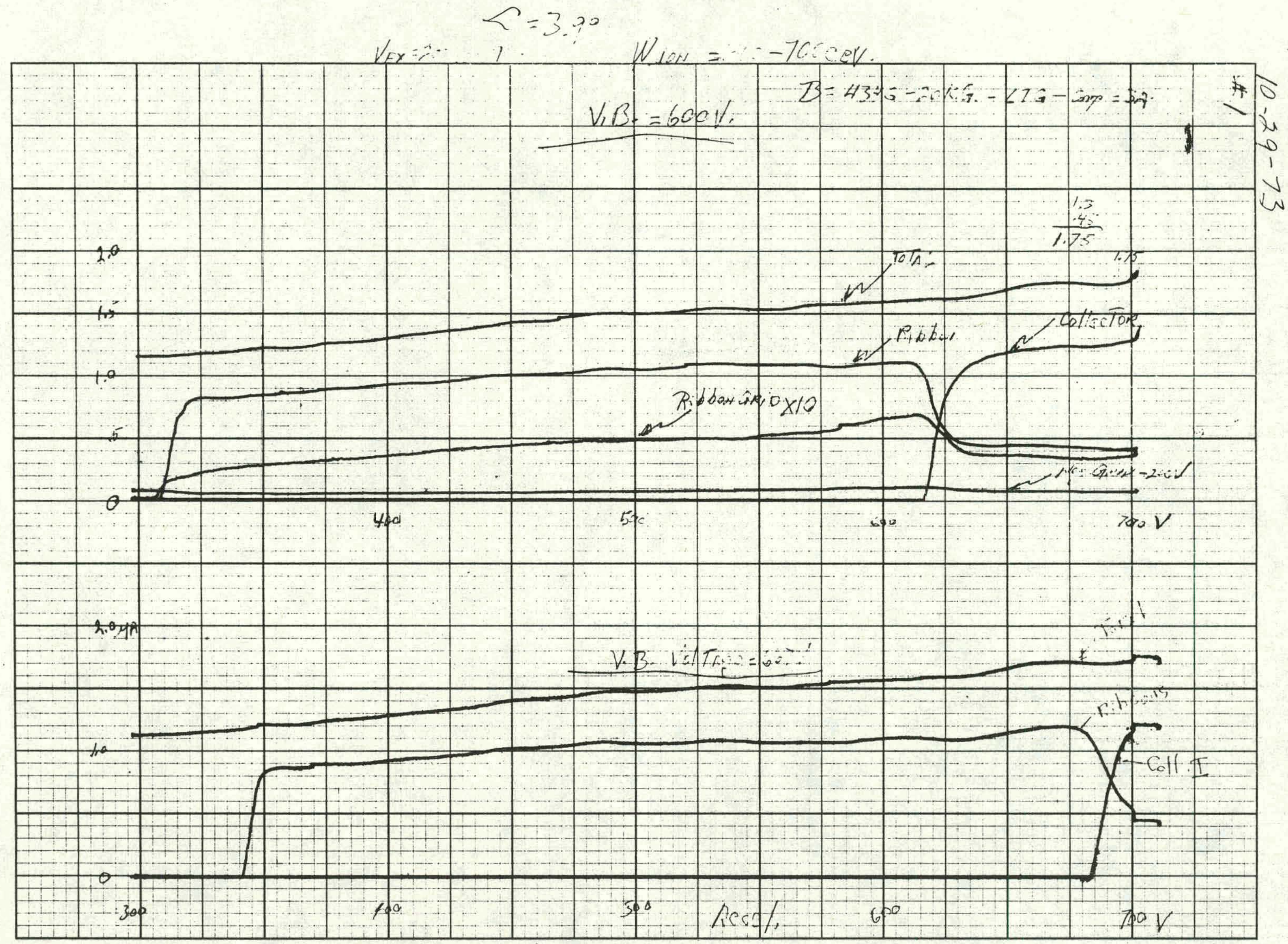


Fig. 7. Collected currents versus $V_2$ for entrance angle, $\alpha_0 = 3.9°$.

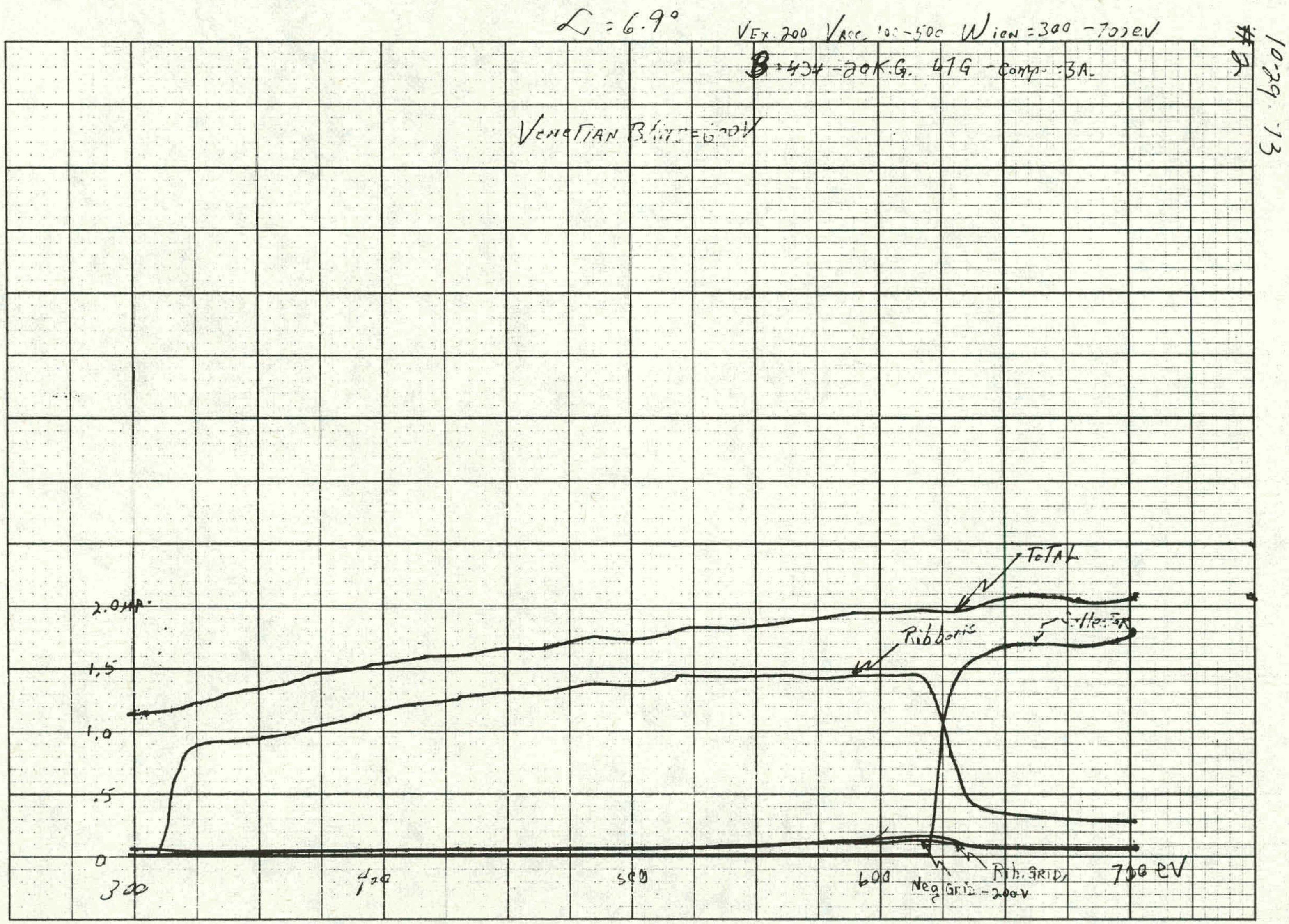


Fig. 8. Collected currents versus $V_2$ for entrance angle, $\alpha_0$ = 6.9°.

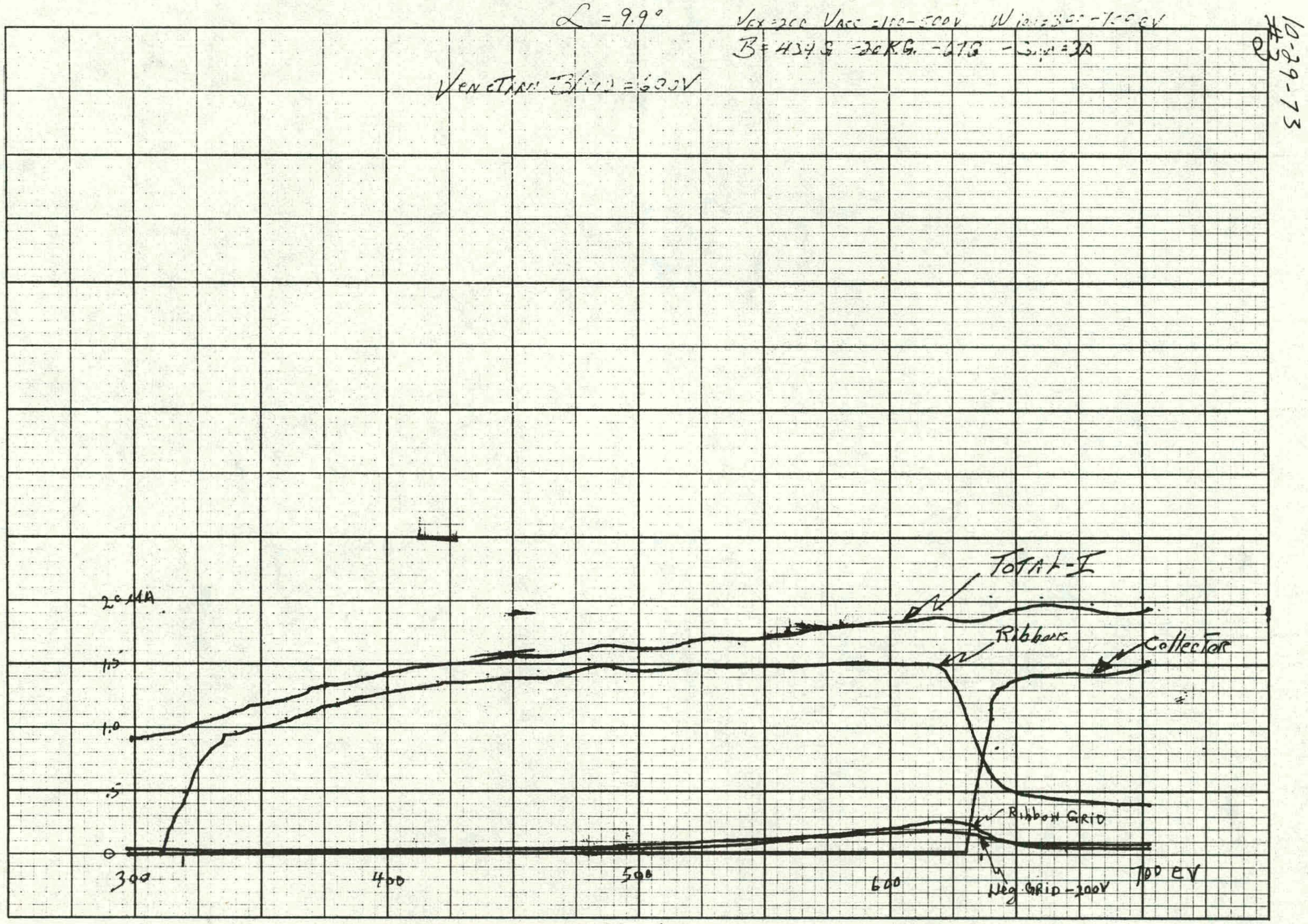


Fig. 9. Collected currents versus $V_2$ for entrance angle, $\alpha_0$ = 9.9°.

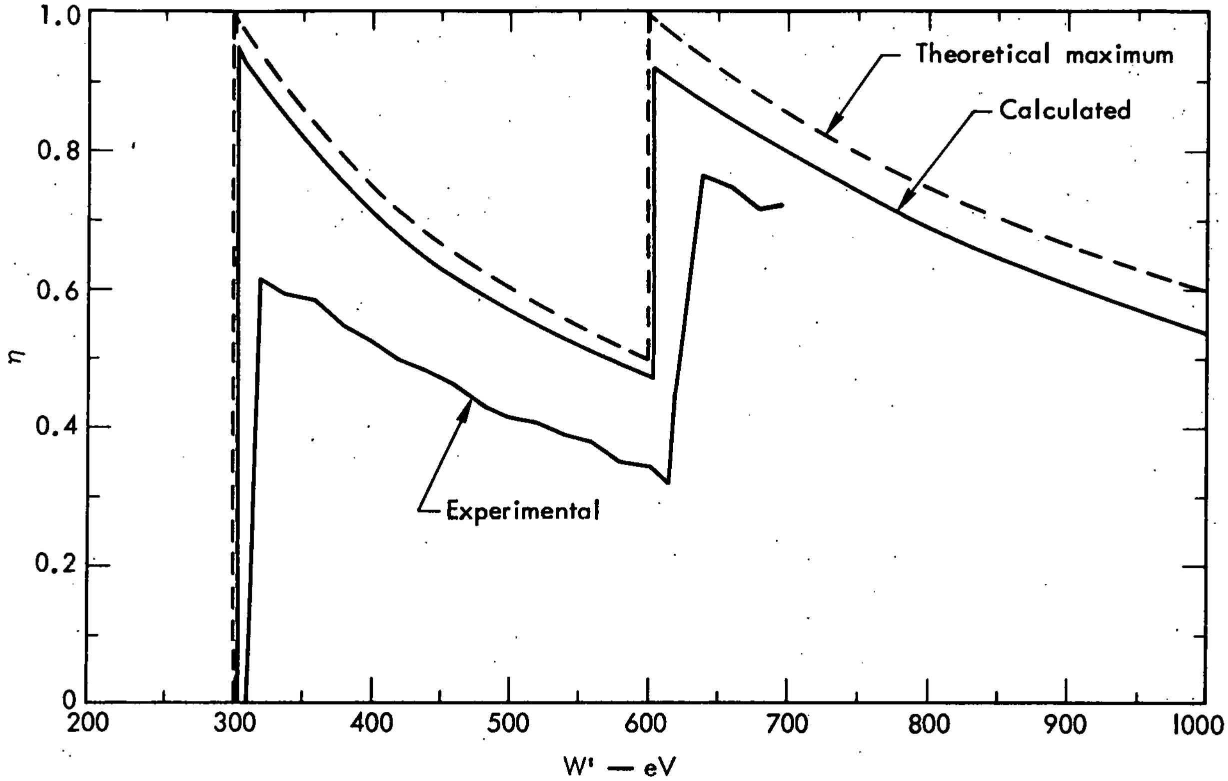


Fig. 10. Efficiency versus hydrogen ion beam energy for $\alpha_0 = 3.9°$.

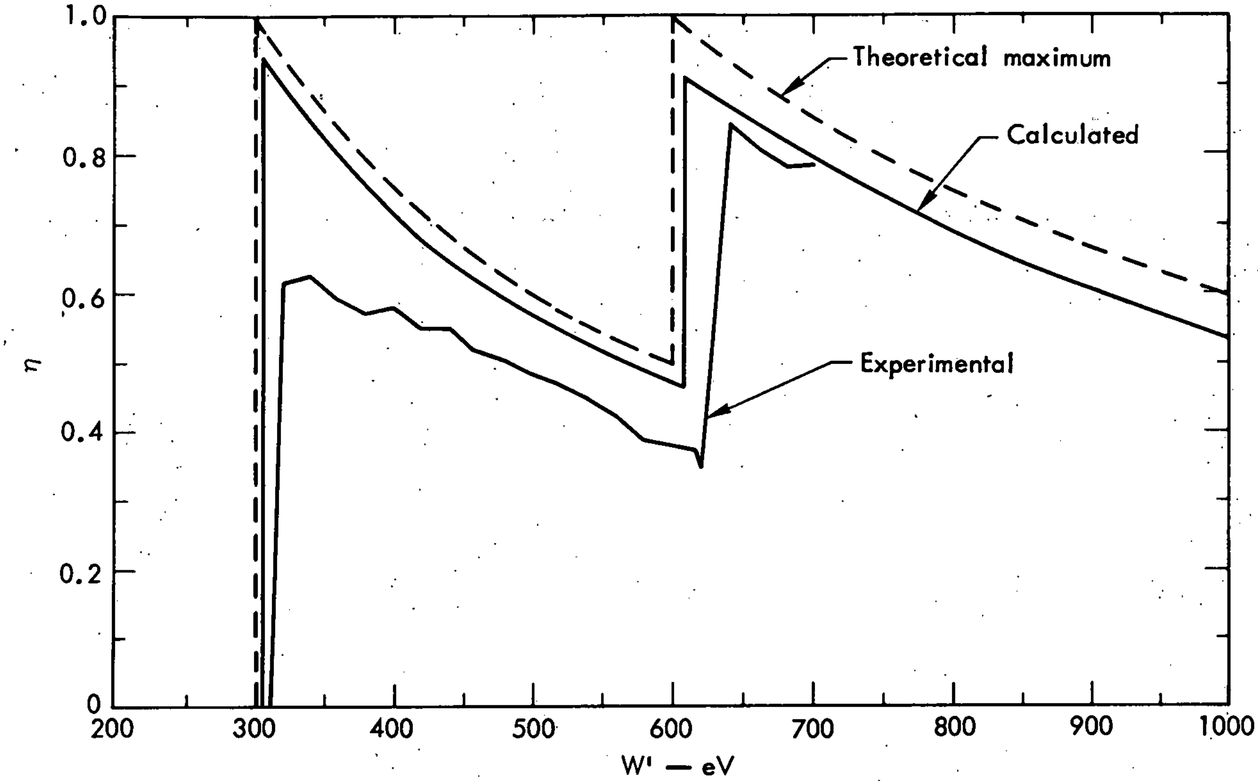


Fig. 11. Efficiency versus hydrogen ion beam energy for $\alpha_0 = 6.9°$.

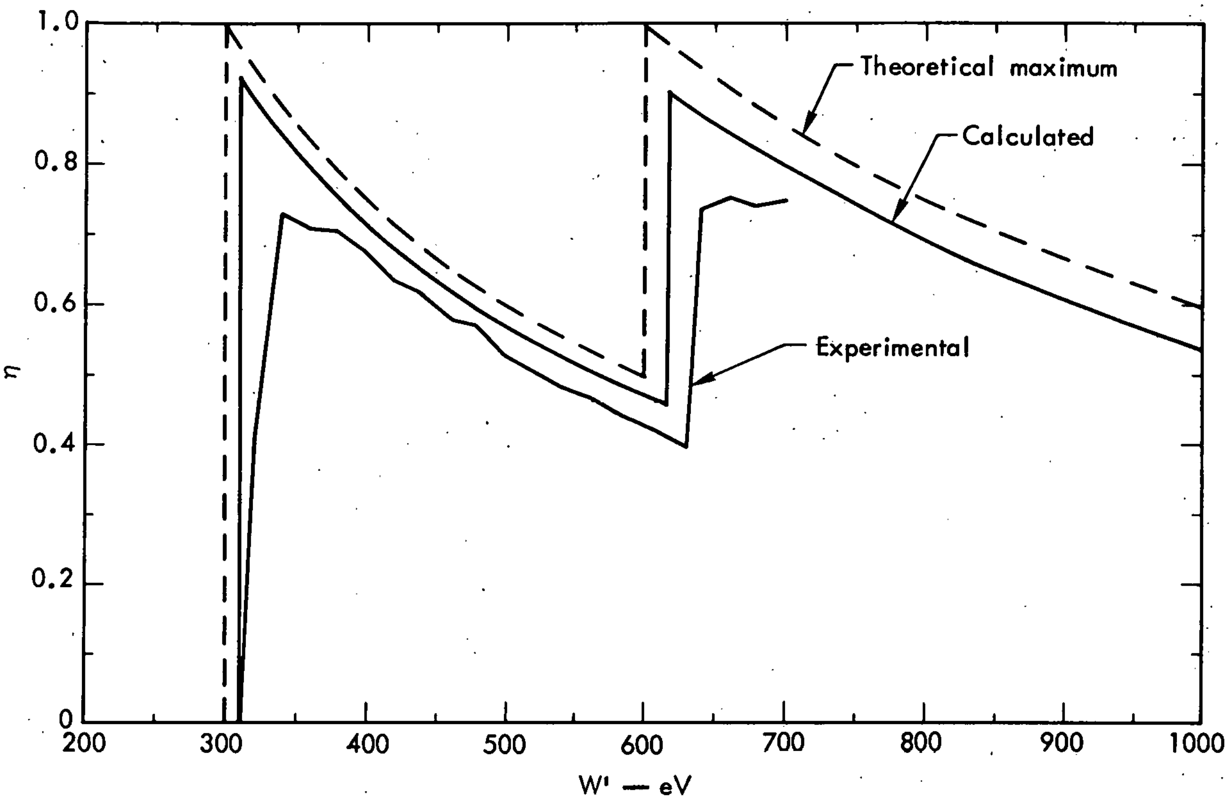


Fig. 12. Efficiency versus hydrogen ion beam energy for $\alpha_0 = 9.9°$.

in fact is offset by a small amount and is rounded off. Here again we speculate that the fringe spreads the angle which then leads to a spread in parallel energy.

The current collected by the negative grid varies over the energy range and is seen to decrease by almost a factor of 2 between 600 and 700 eV for 9.9°. The variation is less pronounced for smaller angles. This could be due to some ions being reflected from the ribbons and hitting the negative holder frame. The current on the negative grid should be given by

$$I_{neg\ grid} = I_{total}(1 - T)(1 + \gamma),$$

where $\gamma$ is the secondary emission coefficient and T is the transmission.

The optical grid opacity (1 - T) is 0.008, but since it is negative the ions will be pulled in giving it a larger effective size. Past experience indicates the opacity is almost twice the optical opacity. From Fig. 7 we have $I_{neg\ grid} = 0.1\ \mu A$, $I_{total} = 1.6\ \mu A$, and $1 - T = 0.016$ at 600 eV. Therefore, the secondary emission coefficient must be 2.9. At 400 eV, $\gamma = 1.9$. At an angle of 9.9° the calculated $\gamma$ is 5.1, which clearly seems too high. This lends further weight to the idea that some returning ions are being caught on the grid holder due to deflection by fringe fields. At 400 eV, $\gamma$ is 0.3, a much more reasonable value.

The ribbon grid should only intercept a fraction (1 - T) of the ions passing on to the collector and a fraction (1 - T) of the ions collected on the ribbon from the back side. At 650 eV no ions should reflect so the current on the ribbon grid should be given by

$$I_{ribbon\ grid} = I_{coll}(1 - T)(1 + \gamma)$$

giving $\gamma = 0.9$. At 600 eV most (80%) of the ions collected on the ribbons should do so from the back sides giving

$$I_{ribbon\ grid} = 0.8\ I_{ribbon}\ [1 - T + T(1 - T)](1 + \gamma).$$

The value of the $\gamma$ calculated here is 1.3.

Although we used stainless steel, the secondary emission coefficient value of 0.2 (Ref. 7) for uncleaned copper and 100-eV $H^+$ can be taken as a useful approximation. Since our beam is a mixture of $H^+$, $H_2^+$, and $H_3^+$ we cannot tell what $\gamma$ to expect, but a value of about 0.2 to 0.4 seems reasonable. A numerical trajectory study would give a good value of (1 - T) and the currents striking these grids. It seems that the grid currents are somewhat higher than expected.

The last run that was made varied the ion energy from 333 eV to 1000 eV. The results are shown in Figs. 13 and 14. For some unexplained reason the ribbons and grids collected too much current with the result that the overall efficiency was poor. This problem will have to be resolved in further tests.

## REACTOR CONSIDERATIONS

The results presented here are quite preliminary and seem to indicate that (at least at low energies) the concept works nearly as well as predicted. In our report on the engineering design[2] we discuss losses not associated with the converter such as coupling to the reactor, charge exchange, and pumping power. All these reduce the efficiency. In that paper we also discussed the recovery of the heat generated in the converter. Our present estimate for recovery of leakage plasma from a mirror reactor including all these effects is given in Table 1. It should be emphasized that a converter based on the one stage concept should be much cheaper to build than converters based on multistage concepts because of the necessity of holding reasonably close tolerances on the ribbons.

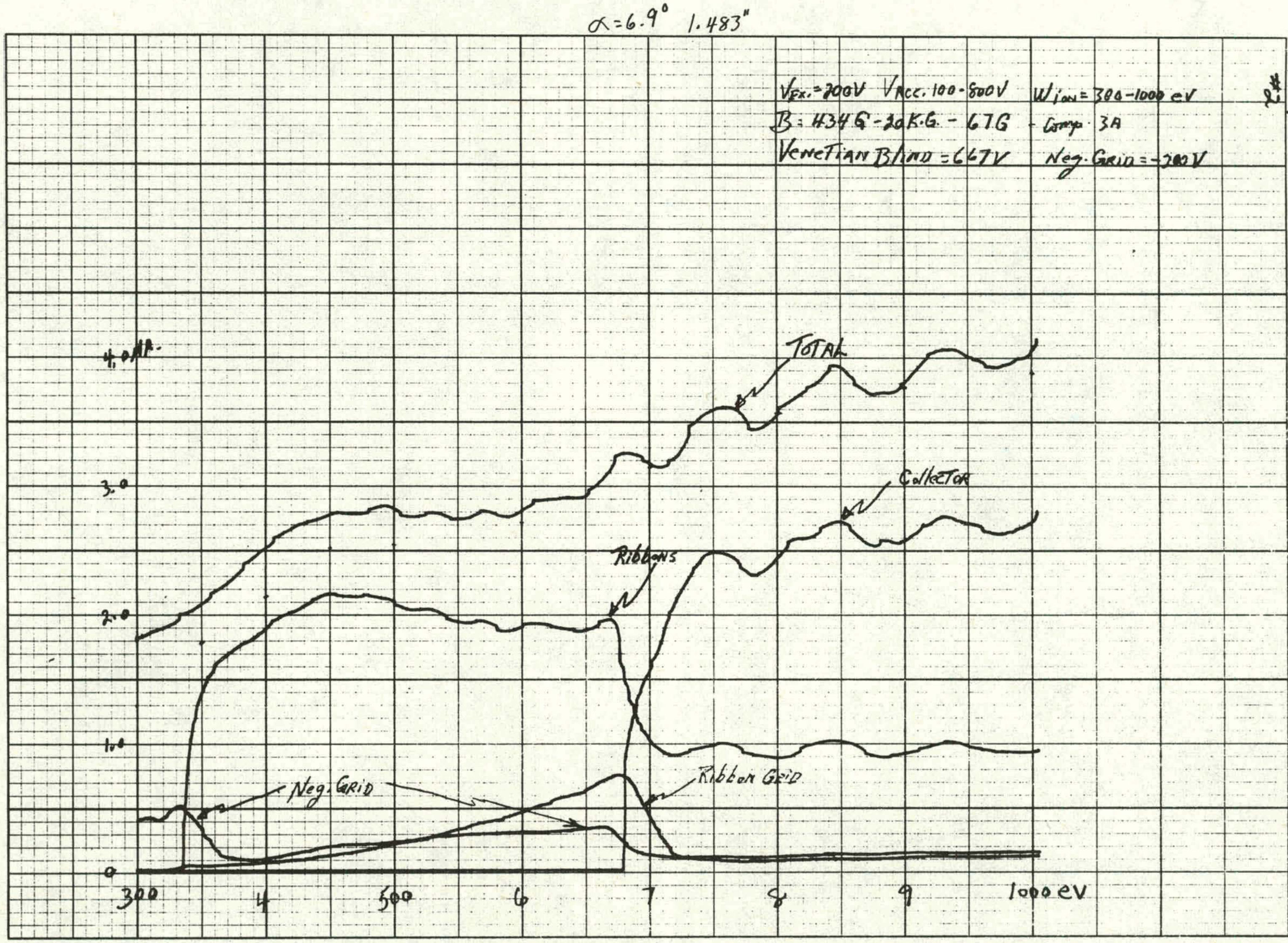


Fig. 13. Collected currents versus $V_2$ for $V_2$ up to 1000 eV.

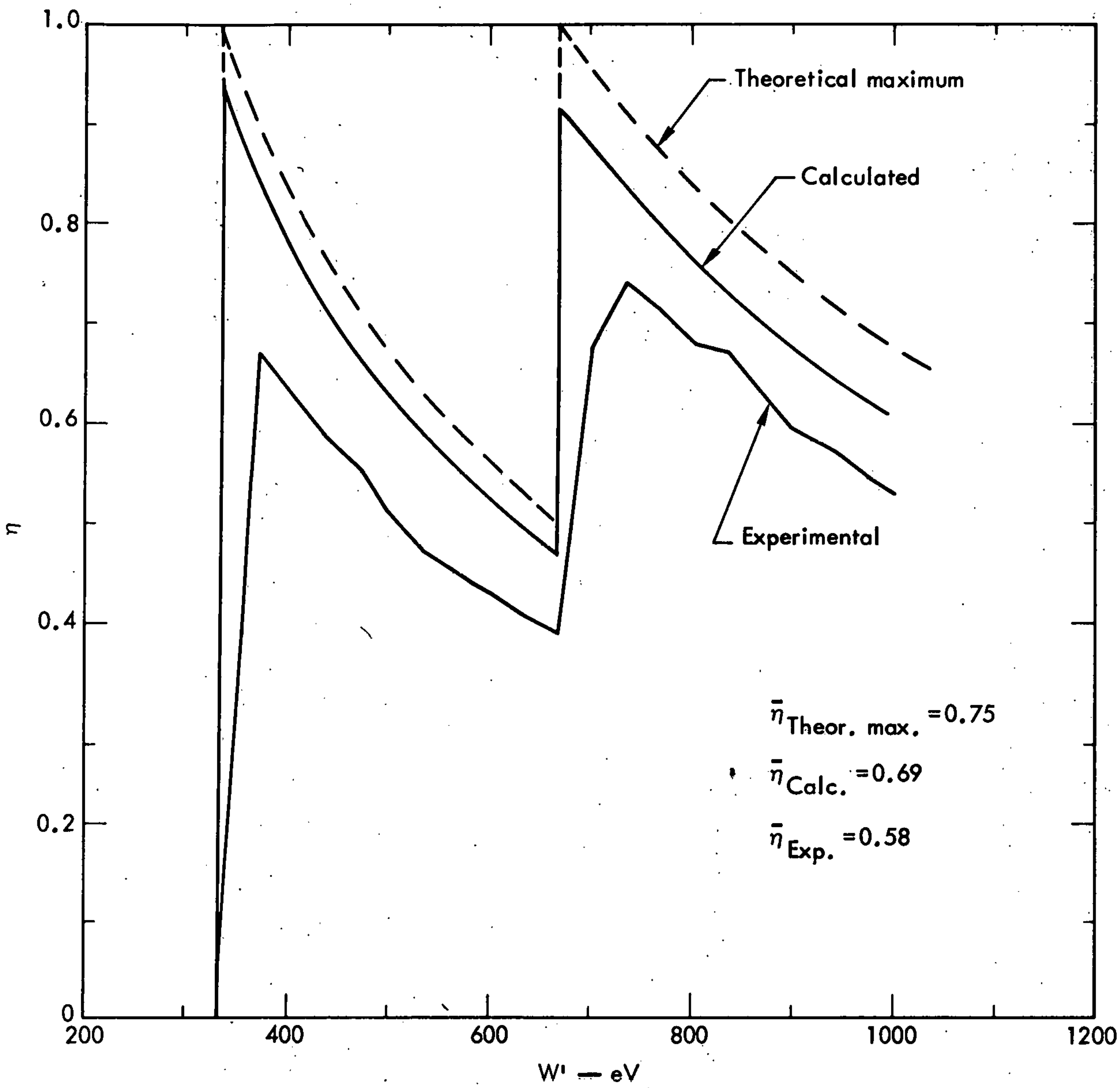


Fig. 14. Efficiency versus beam energy from 333 eV to 1000 eV.

Table 1

| Stages | η (collection) | η (including 40% thermal bottoming cycle) |
|---|---|---|
| 1 | 48% | 68% |
| 2 | 59 | 74 |
| 4 | 65 | 78 |

## CONCLUSION

We have made preliminary measurements on the two-stage, direct energy converter and find that extra losses occur. We speculate that these extra losses are partially due to fringe fields around grids and ribbons and partially due to imperfections in the ribbon electrode spatial orientations. The calculated efficiency was 69% and the measured efficiency was 65%. Our next experiments will be aimed at understanding the discrepancy and hopefully reducing it.

Calculations using the DART code and the two-zone potential relaxation technique for treating potentials that very drastically in space near the grid wire and ribbon edges will shed much light on the behavior of the converter.

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