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UCRL - 75174
PREPRINT
Conf- 731114- - 25

24,986

LAWRENCE LIVERMORE LABORATORY
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APPARATUS FOR TESTING DIRECT ENERGY CONVERSION OF PLASMA ENERGY TO ELECTRICITY

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November 6, 1973

This paper was prepared for submittal to
the Proceedings of the Fifth Symposium
on Engineering Problems of Fusion Research

APPARATUS FOR TESTING DIRECT ENERGY CONVERSION OF PLASMA ENERGY TO ELECTRICITY*

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Abstract

The Lawrence Livermore Laboratory program for research and development of direct energy conversion for fusion reactor application is described. A new test facility consisting of a system of magnets, a vacuum chamber, and collector structure of unusual shapes and sizes is described. Under laboratory conditions, the anticipated collection efficiencies are 65% for a 2-stage venetian blind collector concept and 89 to 90% for a 22-stage periodic focussing concept. Because of space charge considerations, the venetian blind concept appears to be appropriate in the 100- to 200-keV ion energy range whereas the periodic focussing concept is more interesting in the 500- to 800-keV range.

Introduction

Techniques for converting plasma energy to electrical energy are being developed at the Lawrence Livermore Laboratory. The physical processes involved are as follows:

1. Divert and expand the leaking plasma so as to reduce the power flux density (W cm^{-2}) and to obtain directed motion
2. Separate the electrons from the ions
3. Decelerate and energy separate the ions
4. Collect the ions on high-voltage electrodes

A method for direct energy conversion employing a fan shaped expander and a periodic focussing decelerator structure was proposed by Post.[1] The concept, considerably refined,[2] is shown in Fig. 1 taken from the work by Smith et al.[3]

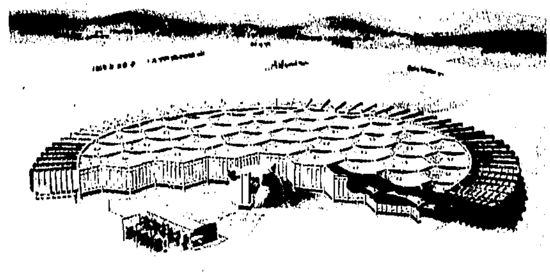

Fig. 1. Conceptual direct energy convertor: fan shaped expander and periodic focussing collector.

Another method employing a conical shaped expander and a set of ribbon grids resembling venetian blinds was proposed by Moir and Barr[4] and further studied by Barr et al.[5] (Fig. 2).

Experiments of the periodic focussing concept resulted in 83% of the energy of a 300- to 1000-eV lithium ion beam being recovered in electrical form.[6] The experiments did not test the expander (1 above) or electron separation (2). The apparatus shown in Fig. 3

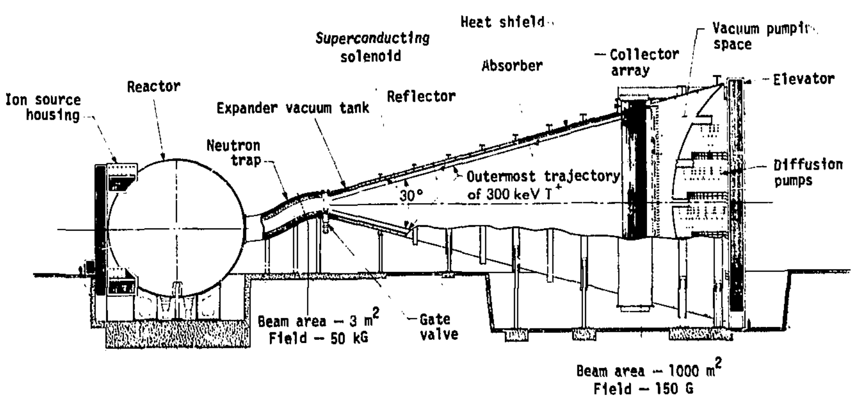

Fig. 2. Conceptual design of direct energy converter: conical shaped expander and venetian blind collectors.

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

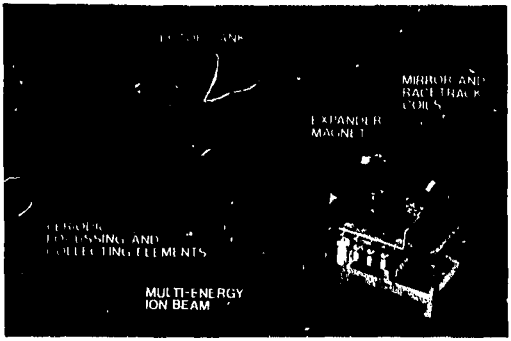

Fig. 3. Direct conversion test facility.

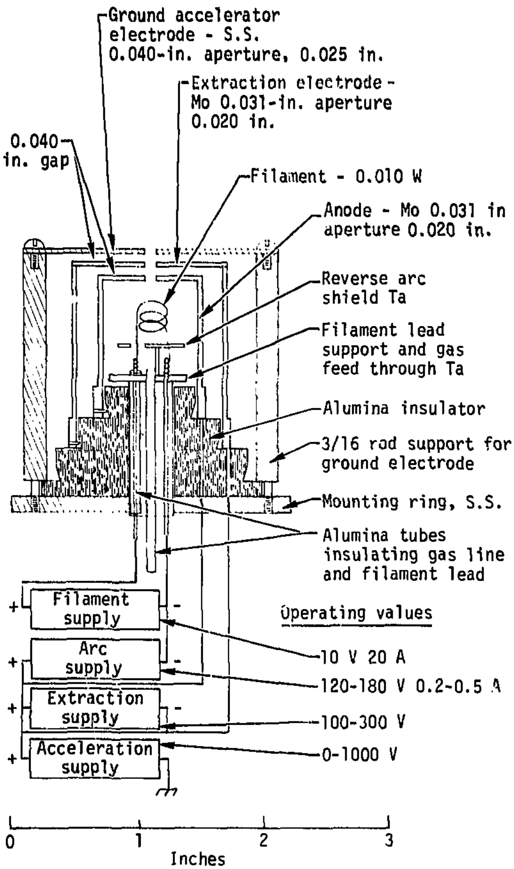

Fig. 4. Ion source. This source is designed to run hot (~2300°K) to maximize the H^+ species by dissociation of H_2 and to have a high gas efficiency.

has been built to test the physical processes involved in direct energy conversion. The principal components are, the ion source (a plasma source is being developed), the magnetic expander and separator, and the decelerator and collector structure.

Ion Source

The ion source (Fig. 4) was developed to produce a microampere beam of 300-eV hydrogen ions with a minimum gas flow; it is similar to the coluton[7] source. The source characteristics are given in Table 1. Because the physical dimensions and adiabatic considerations of the magnetic expander limits the orbit size,[8] it was desirable to maximize the H^+ fraction of the beam. This was done by running the walls of the molybdenum arc chamber at 2300 K to enhance the atomic fraction by H_2 dissociation. This extremely high temperature (T_{melt} = 1770 K for stainless steel, T_{melt} = 2880 K for molybdenun) was obtained by the multiple concentric molybdenum shield construction, Further development with hot walls should yield considerably higher H^+ fractions than the 30% noted in the table. Our recent source work has emphasized reliability rather than high-temperature operation.

Magnetic Field Design

The shaped magnetic field coil, shown in Fig. 5 extending from the ion source to the exit end of the expander, was designed with the MAFCO[9] computer code using filamentary conductors that were plotted by a computer code.[10] A cross-section of the mirror and oblong magnet set is shown in Fig. 6. The magnet set and the source magnet shown in Fig. 3 combine magnetically to form a single mirror region in front of the source. The mirror-oblong magnet produces a maximum field of 31.6 kG on axis at 2000 A and is powered at 443 kW. This power is supplied by two 300 kW sources in series.

There are a total of 458 turns of 3/8-in. square hollow conductors wound bifilar into pancakes with separate water-cooled leads from each pancake to provide for the necessary heat dissipation. A common mandrel, which is also part of the vacuum system, supports both coils. Total water flow through the parallel path is 36 gpm at a 60-psi pressure drop and a 47°C temperature rise. The oblong coil is shaped to spread the magnetic field lines

Table 1

Characteristics of Ion Source

Current	20% μa
Fraction H^+	30%
H_2^+	60%
H_3^+	10%
Gas feed rate	4 atm cm^3 hr^{-1}
Gas efficiency	15%
Pressure in source chamber	2×10^{-6} Torr
Arc power	1.5 A 60 V
Filament power	20 A × 10 V
Extraction voltage	300 V
Acceleration voltage	0-700 V
Filament lifetime	16 hr

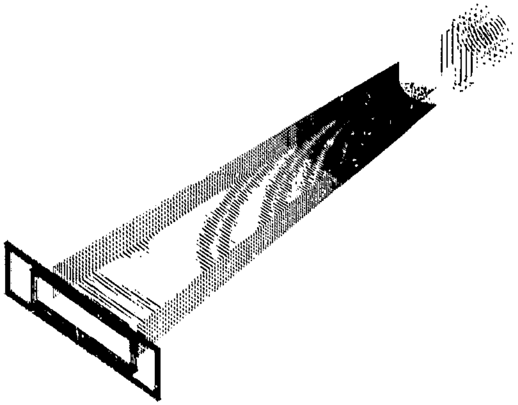

Fig. 5. Filamentary conductors of the magnetic expander.

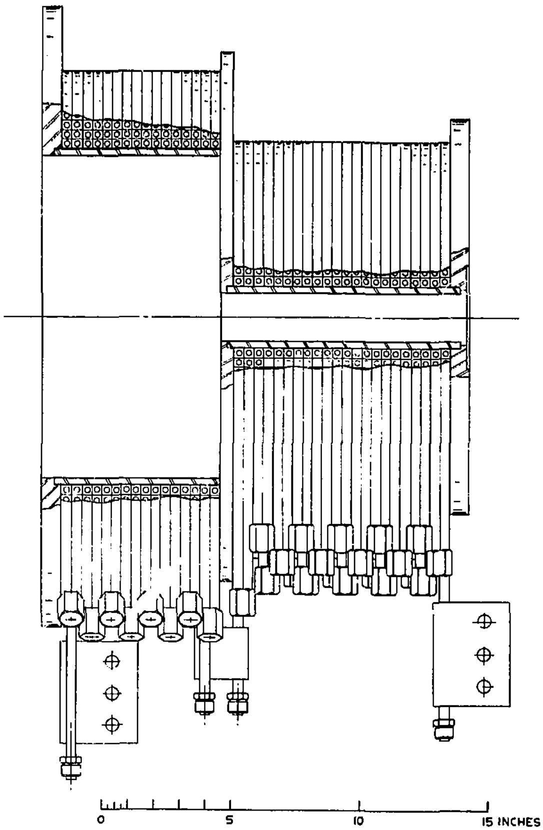

Fig. 6. Mirror and oblong magnet.

horizontally more than vertically. The expander magnet, which is essentially a pie-shaped segment of the much broader fan-shaped expander seen in Fig. 7 acts like a nozzle in converting ion motion from the perpendicular to the parallel direction relative to the magnetic field. A detailed study[9] showed that the field strength must vary smoothly with the axial component falling off no faster than inversely with axial distance and that unusual accuracy in placing the conductors within the expander region was required to keep the field lines colinear with the metal walls at the expander vacuum chamber. The locational accuracy at the 163, 1/4-in. square hollow conductor turns of this magnet, which is wound counterclockwise around the vacuum chamber, has been accomplished by the use of grooved epoxy-fiberglass laminate plates that have been machined by a tape controlled mill. In this manner, the location of the upper and lower same turn conductor faces have been placed within 0.015 in. of each other and at the proper between-conductor spacing to produce the required field graduation.

This magnet is powered by a supply operating at 37 V and 200 A which gives a field at the expander exit of 100 G. The maximum-to-minimum field ratio through the expander is then 300. The field is abruptly brought to zero with the diverter-separator coil set shown in Fig. 7. The electrons, having a small larmor radius, will follow the field lines and be pulled out of the plasma beam whereas the ions, being massive, will continue forward into the collector with only a slight deflection.

The divertor-separator coils have been canned and their leads exit through separate flange ports in the expander ring chamber face. The innermost end coil is a 24 turn 3 × 8 conductor cross section magnet. A 25-turn-separator coil with a 5 × 5 conductor cross section is located around the divertor coil. Both of these coils are formed from 1/4-in. square hollow conductor and are hydraulically independent. All three expander windings are electrically in series and are powered by the same supply mentioned before.

Vacuum System

The vacuum system was designed to be oil-free to avoid contamination of the collector surfaces and to operate in the low 10^{-7} Torr range to minimize charge-exchange losses. A

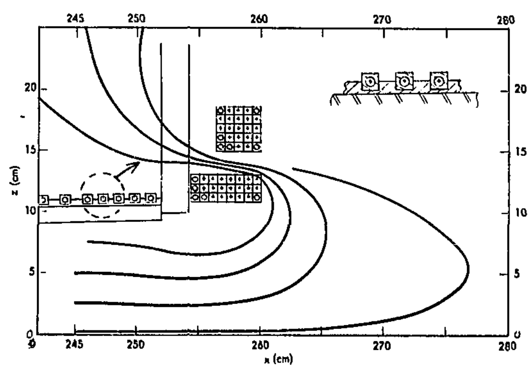

Fig. 7. Divertor-separator coil set.

combination of ion pumps, gettering, and sorption pumping are used to maintain the high vacuum. Two mechanical carbon vane pumps followed by sorption pumping provide the initial rough vacuum.

Three basic parts of the vacuum system are those of the mirror-oblong magnet set (which has been described), the expander, and the collector. The mirror-oblong magnet set is the volume on the source side of the beam collimator. This is pumped by a 500 liter/sec vac ion pump with an operating pressure of 2×10^{-6} Torr. A valve on the source side of the strong magnet allows the source to be changed without affecting vacuum in the main system. The source pumping section has an independent cryosorption manifold of four 4-in.-diameter pumps plus connections for carbon vane roughing pumps.

The expander-collector tank volumes are common and are pumped by two 500 liter/sec ion pumps, and two cryosublimator pumps of 6000 liter/sec and 5700 liter/sec pumping speed, which are conductance limited by the 7-in.-diameter valve and optical baffling. This produces a vacuum of less than 2.0×10^{-7} Torr. This section of vacuum system has a manifold with four 9-in.-diameter cryosorption pumps and roughing line for carbon vane pump.

The expander vessel is a trapazoidal shaped chamber that was fabricated from two channel halves whose shape expands in two directions. The corners of the 1/2-in. plate channel halves were formed with a 2-in. radius to avoid a sharp bend of the conductor. These channel halves were then seam-welded to form the trapazoid vessel section. A plenum section at the source end of the expander provides a tie to the flange of the coil set and has provision for pumping at the lower end and a port at the top for diagnostics. The downstream end is a 4-ft-diameter ring that matches the collector tank and houses the two end coils. Pumping and diagnostic ports are also located in this area. Additionally, the trapazoidal section has a pair of 2-in.-wide, full-height diagnostic ports on each side.

The collector section of the machine consists of a 10-ft-long 4-ft-diameter tank that houses a 22 module system, which electrostatically decelerates, focuses, and collects the positive ions at different energy levels (Fig 8). These modules mount in a rack that ties to the end flange of the tank and has rollers at one end to permit disassembly of these two units for access to these modules. All leads from the modules pass through an adjacent vacuum seal into a 3-in.-diameter tube that runs parallel and adjacent to the modules. Provision has been made for pumping of this tube in the event of a leak.

Collector Design

Periodic Focussing

Cross-sections of the collectors are shown in Fig. 8 and an overall view is shown in Fig. 9. The stainless steel grid wire diameter is 0.0[illegible] in. Detailed trajectory calculations were done using the DART code,11 which was de-

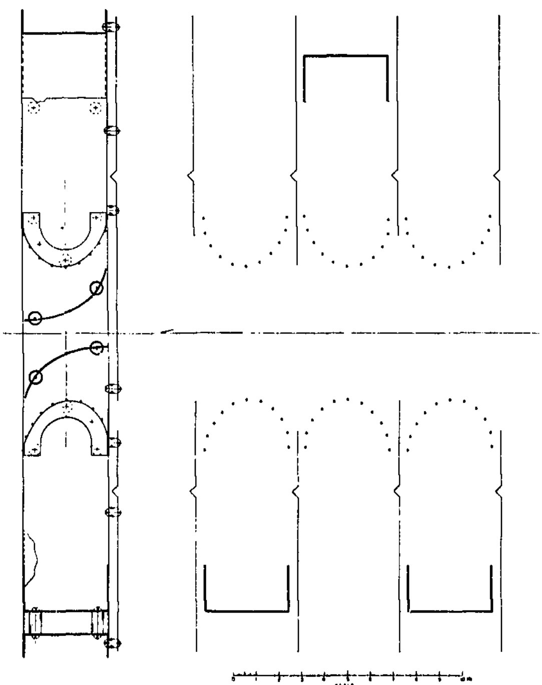

Fig. 8. Collector cross sections (a) showing insulators and curved potential forming electrodes and (b) as seen by beam.

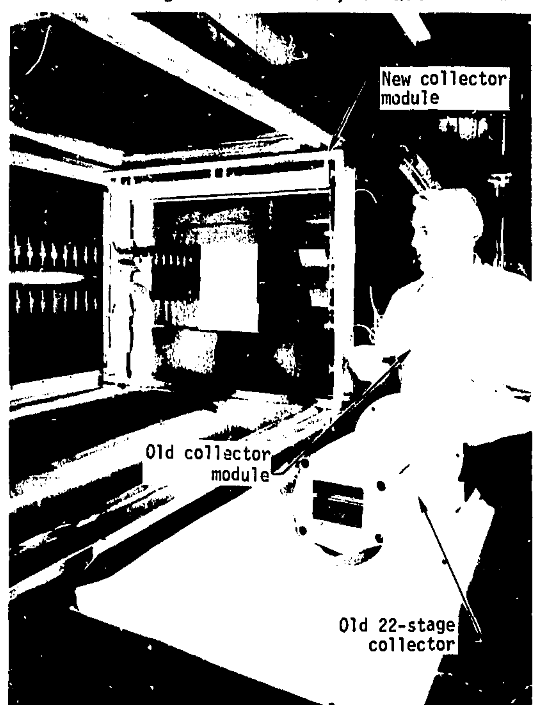

Fig. 9. Collector module. Note the small module and the 22-stage collector device described in Ref. 6.

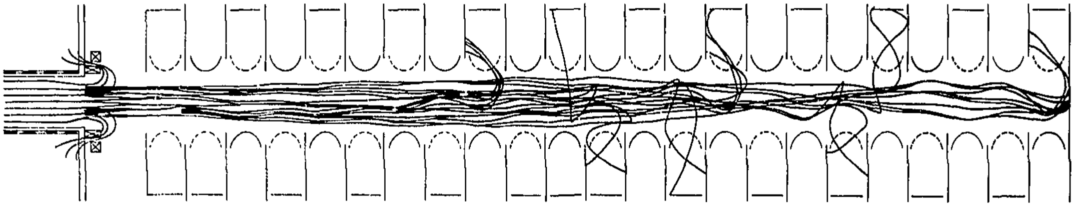

Fig. 10. Trajectories in collector computed and plotted by the DART code.

veloped to design the direct converter and to simulate its behavior. An example of these trajectory calculations is shown in Fig. 10. There are 23 modules. The first one is a negative stage to repel electrons, the second is a collector with one half the focus strength to keep the beam centered, and the other 21 are full focus strength collectors making 22 collector stages.

Venetian Blind

Although the design of a direct energy converter using the venetian blind concept calls for a conical expander, the present device (Fig. 3) can easily accommodate this type of collector at the end of the expander. The 2-stage venetian blind collector structure is shown in Fig. 11 and a cross-section with sample trajectories is shown in Fig. 12. The grids are made of 0.001-in.-diameter tungsten wires and the ribbons are 0.011- by 0.625-in. stainless steel.

Electronic Measurements

A gridded energy analyzer is used to measure beam current just after the oblong coil. A segmented gridded analyzer is used to obtain the spatial profile of the beam at the end of the expander near the ports shown in Fig. 3. The measured profile agrees with the one calculated with the trajectory code.

To measure the current collected on the many collectors where each is at a different high voltage, an isolation device was built to convert the current to a train of pulses whose frequency varies linearly with current over many decades in current. This device and another are described in Ref. 12.

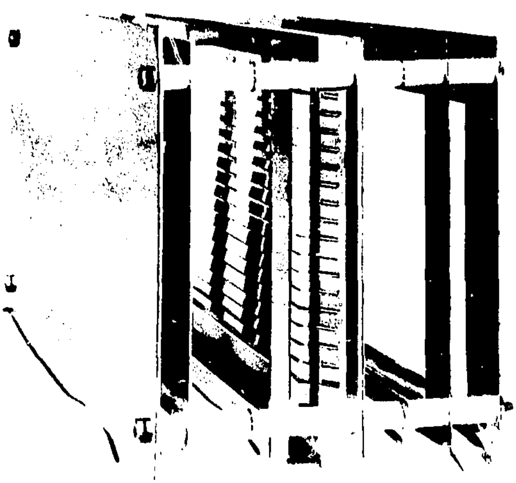

Fig. 11. The 2-stage venetian blind collector structure.

Experimental Results

Experimental results with the periodic collectors are not yet available, however the calculated results are given in Fig. 13. These calculations are discussed in Ref. 13. Preliminary results with the venetian blind collector are shown in Fig. 14.

Future Plans

Our plans are to use the ion source to study the direct converter for low space charge (low scaled power) conditions to understand the details of the collection processes. Underway now is the development of a plasma source

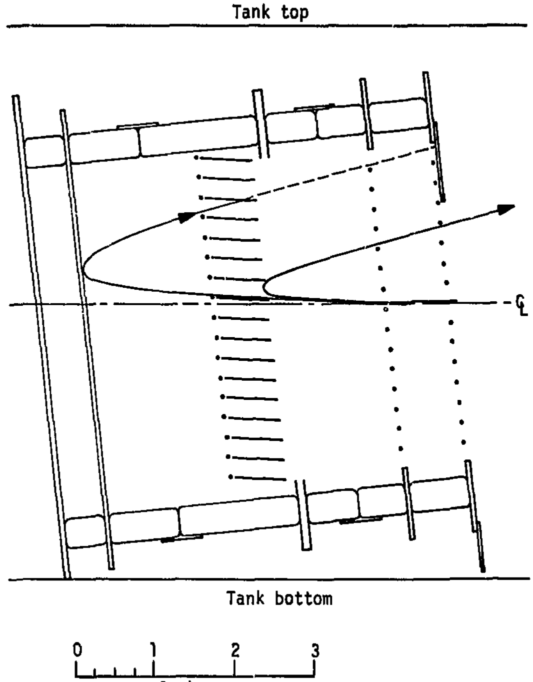

Fig. 12. Cross section of 2-stage venetian blind collector with typical trajectories.

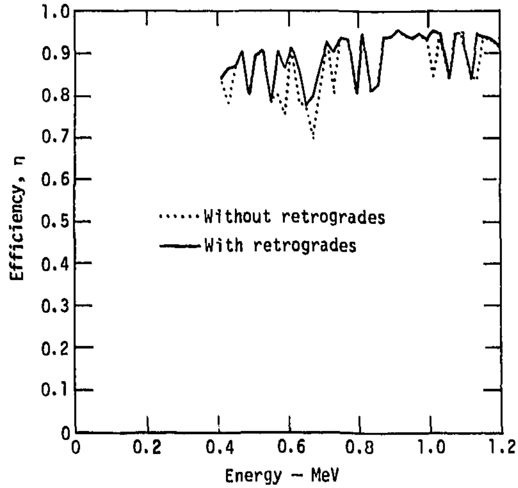

Fig. 13. Efficiency versus energy for the 22-stage periodic focus collector expected experimental condition calculated by the DART code. The parameters for this figure are: $\bar{\eta} = 0.92$, N trajectories = 240, C = 2.5, L = 22.5 cm, ZFIN = 0.33 L and 333 eV $\leq$ W $\leq$ 1000 eV.

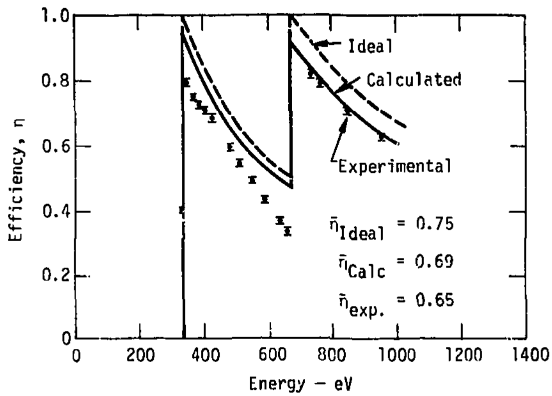

Fig. 14. Efficiency energy for the 22-stage venetian blind collector, experimental and calculated data.

that will allow the investigation of space charge effects. Separate experiments[14] on the voltage breakdown physics are being performed. The experimental investigation of the transfer of energy from electrons to ions in a magnetic expander is also being planned.

Our goal remains to develop direct energy converters that are as efficient as possible and that handle enough power to be economically interesting.

Acknowledgements

We thank C.L. Hansen and W.J. Gould for constructing and assembling the apparatus; A.R. Harvey for discussions on design and fabrication of the magnets; D.D. Schlesser for skillfully winding the magnets; T.H. Batzer for discussions concerning the vacuum system; R.V. Pyle for providing us with an early version of the colutron ion source; and R.F. Post and T.K. Fowler for discussions and support throughout the planning, assembly, and experimental phases of the project.

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